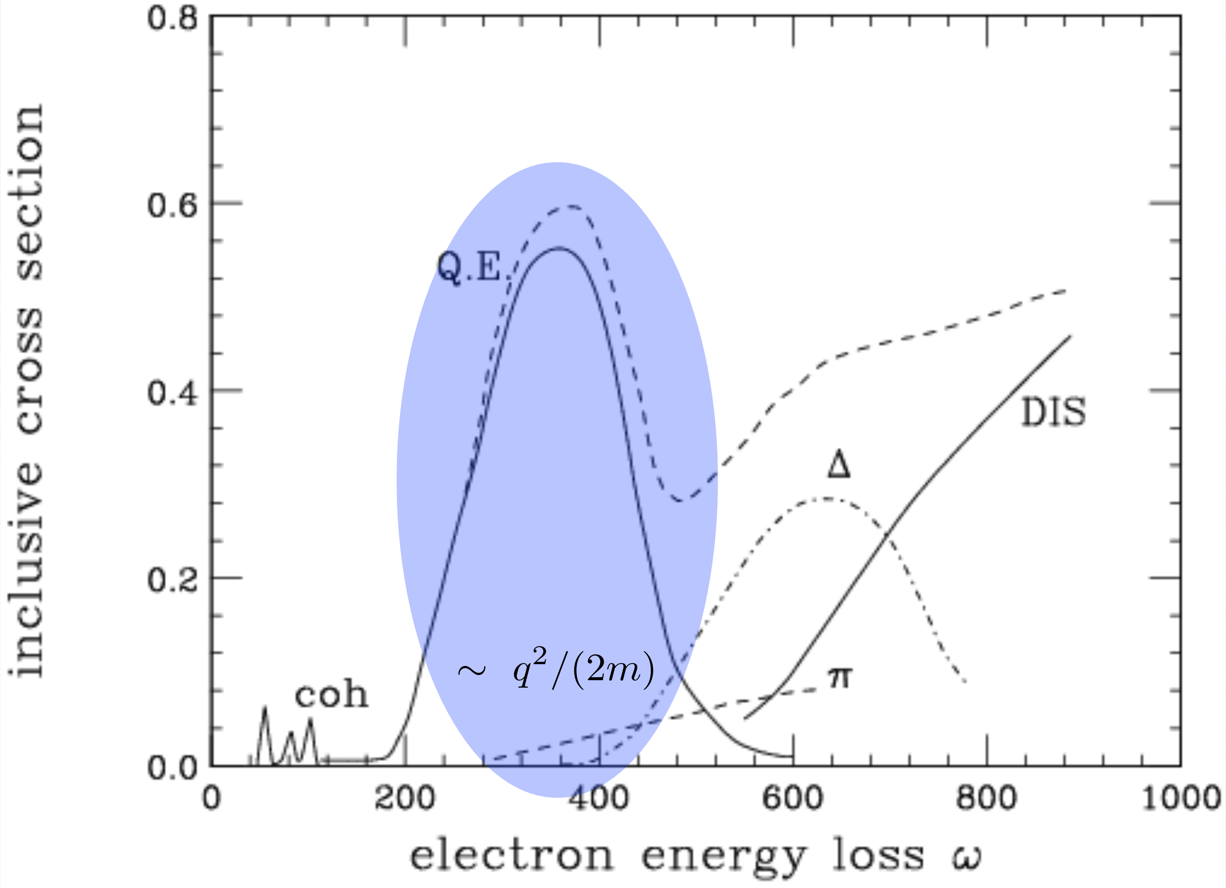
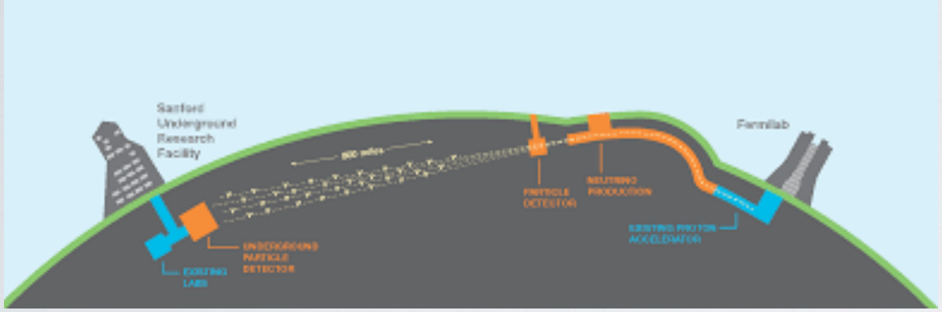
Quasi-elastic (inclusive) neutrino scattering from nuclei

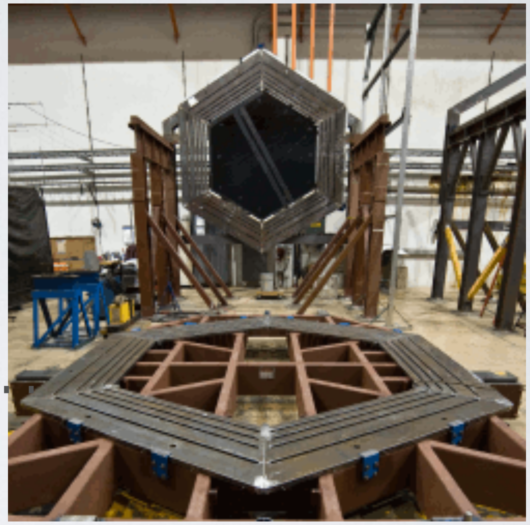
J. Carlson, LANL

S. Pastore
A. Lovato
D. Lonardoni
S. C. Pieper
R. Schiavilla
R. B. Wiringa

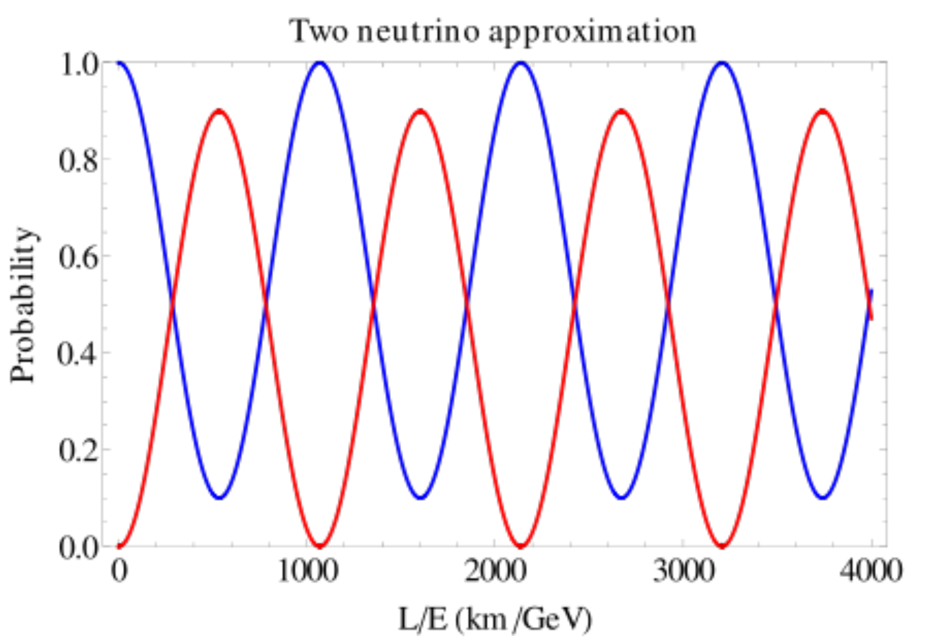


Why study neutrino-nucleus scattering ?



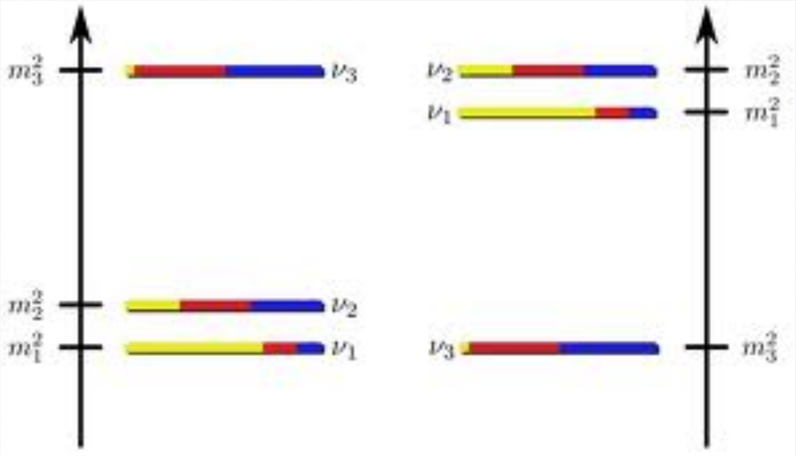


DUNE, Minerva, T2K, Nova, MicroBooNE. .



mass differences,
mixings from oscillations

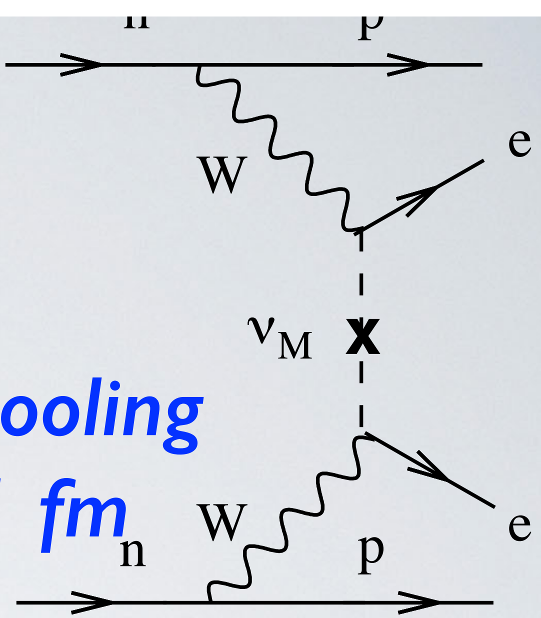
see session later today

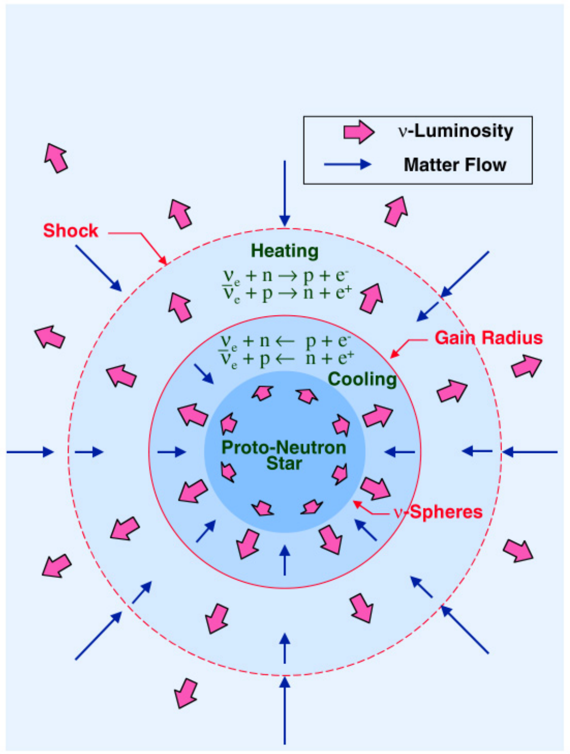


mass hierarchy
CP violation in neutrinos
non-standard interactions
…

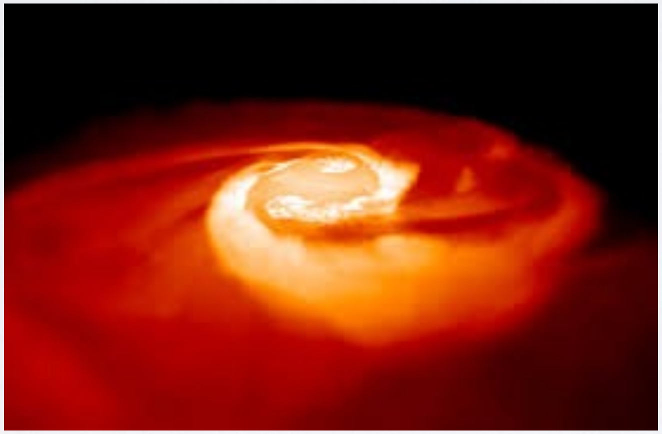
ALSO:

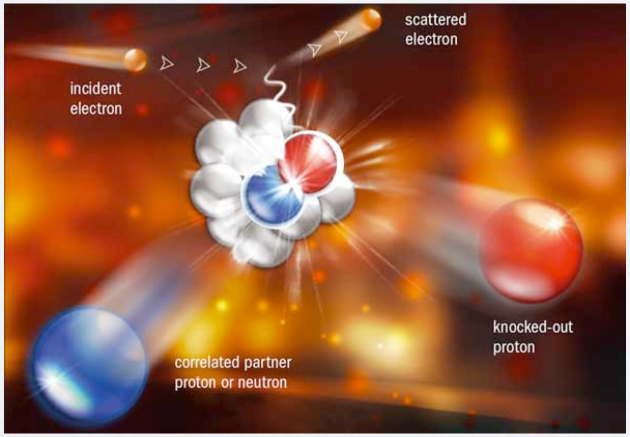
- ***neutrinoless double beta decay,***
- ***astrophysical neutrinos: supernovae***
  neutron star cooling
- ***nuclear structure and dynamics at ≲1 fm***

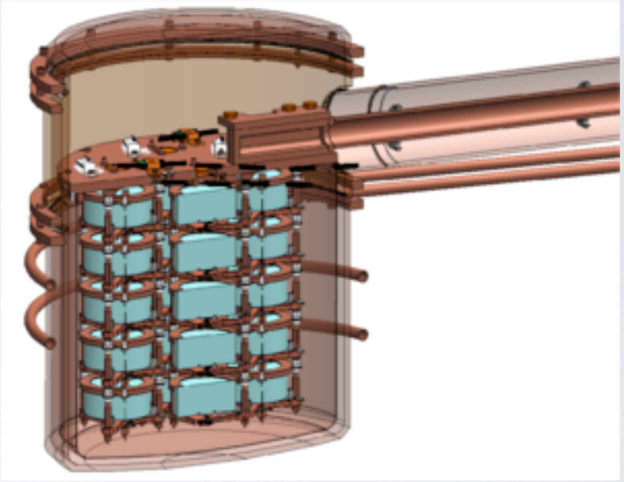


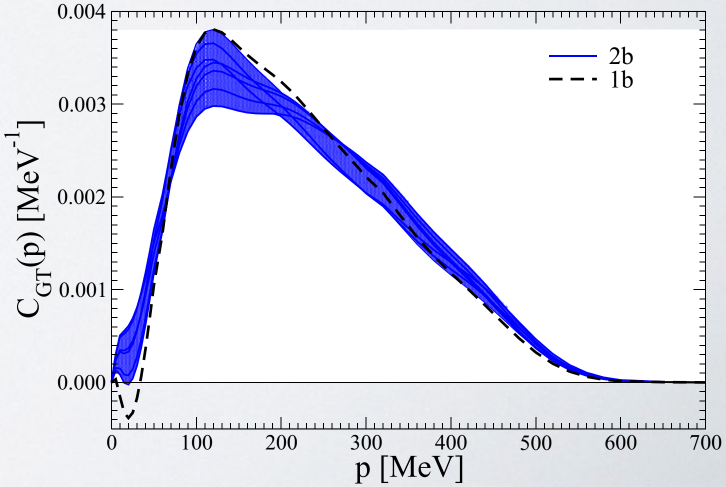


Coherent, Ar, …

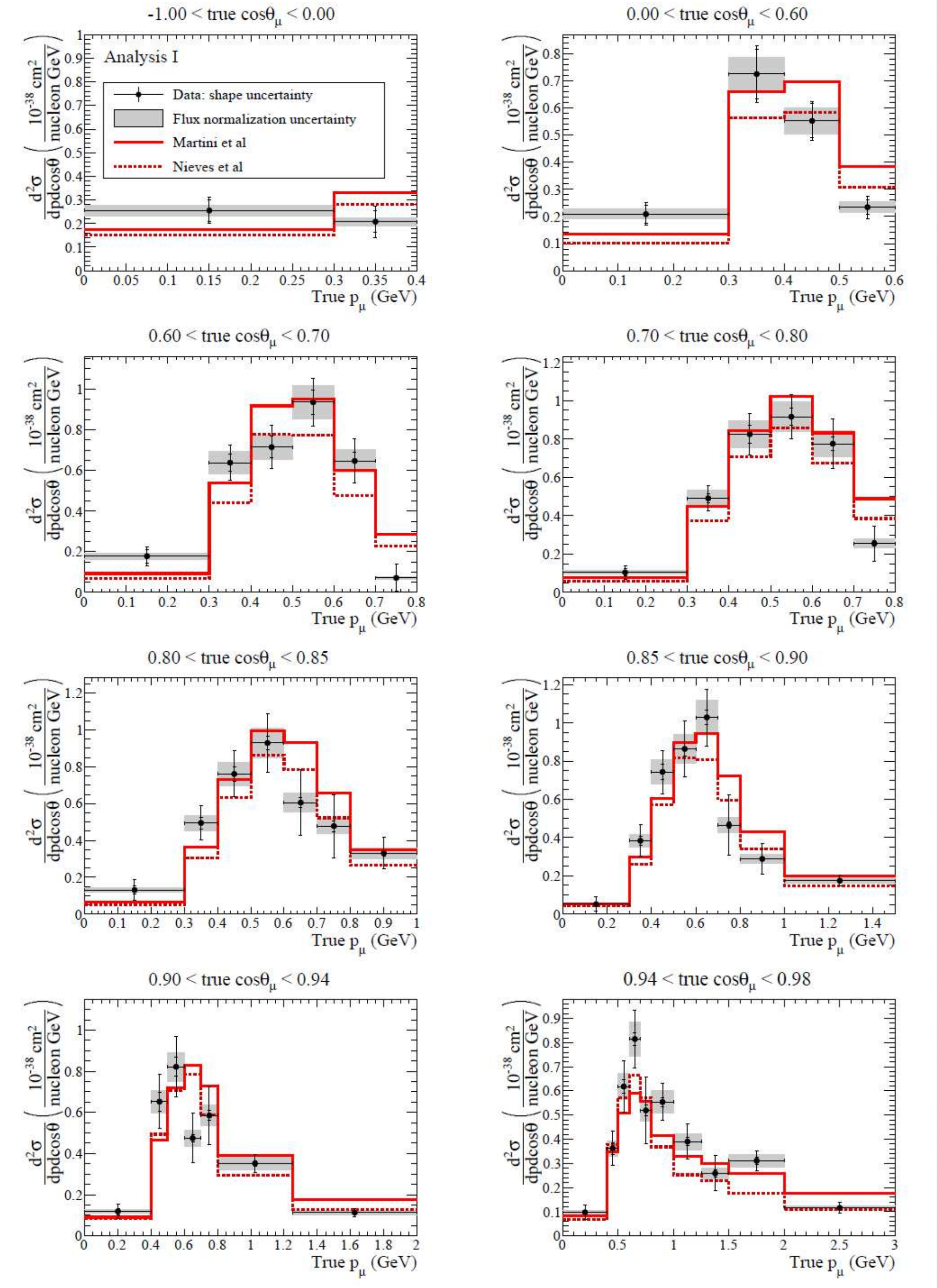








CC 0π on ^{12}C



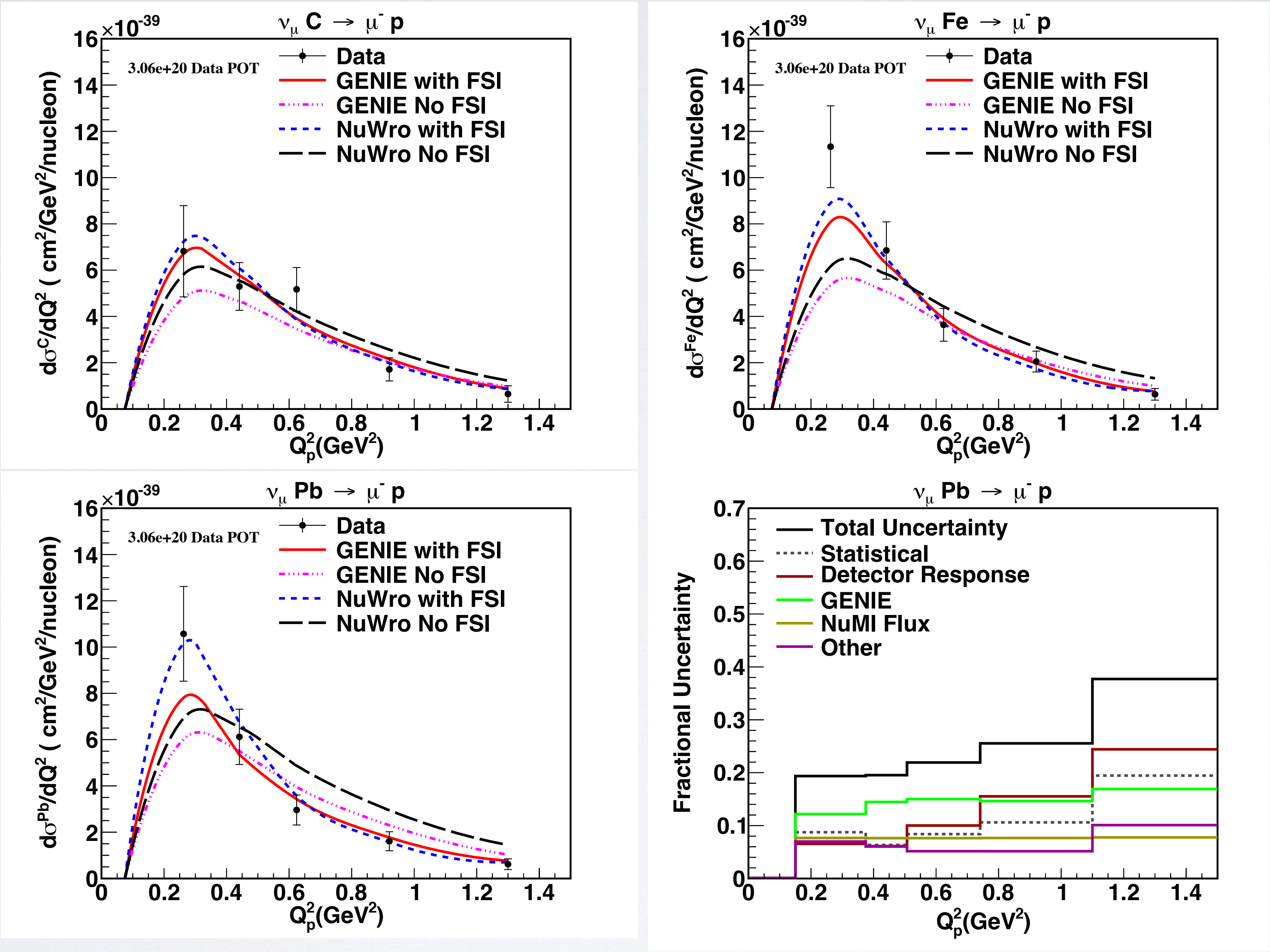
Martini and Nieves RPA
compared to T2K, Abe (T2K collab) 2016

Improved agreement including 2p-2h contributions and enhancement in V, A, & A-V interference contributions

Similar contributions added in SUSA and improve agreement with data

More exclusive data?

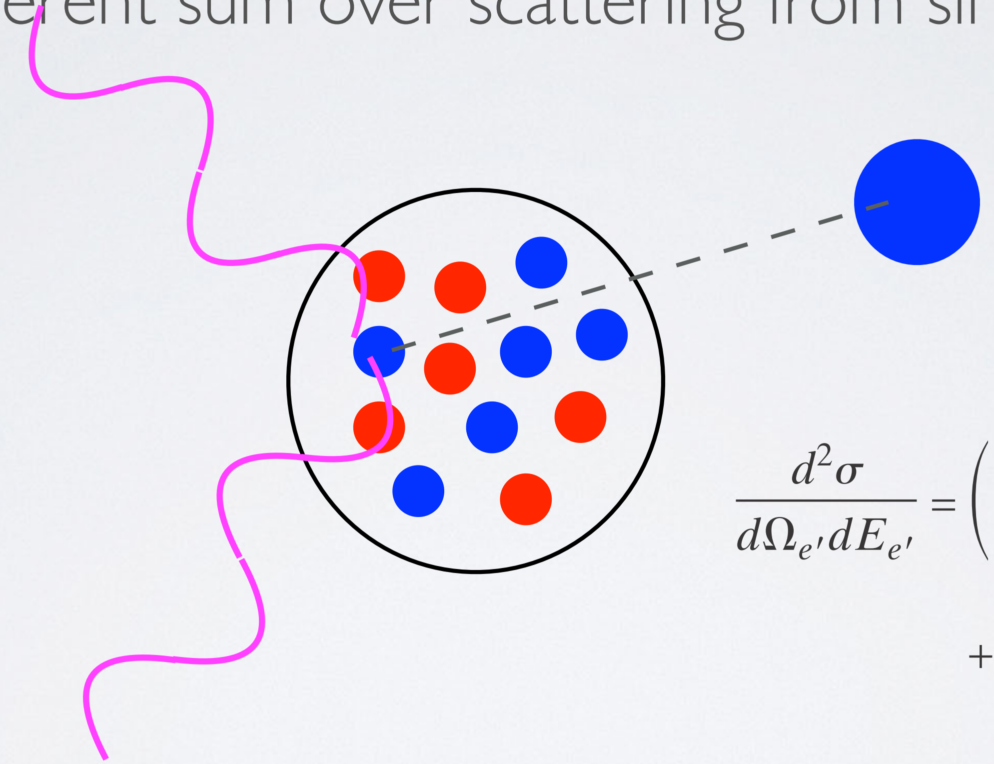
Nuclear Dependence



Minerva results for different nuclei
compared to generators

Quasi-elastic scattering: simplest picture
Incoherent scattering from individual quasi-free nucleons

Scaling with momentum transfer: 'y'-scaling
incoherent sum over scattering from single nucleons



$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4}R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2}+\tan^2\frac{\theta}{2}\right)R_T(|\mathbf{q}|,\omega)\right]$$

PWIA often good for q >> k_F; used in many fields
(neutron scattering, …)

Inclusive Scattering

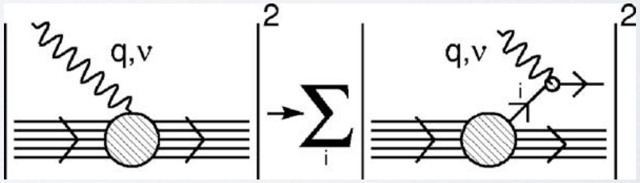
$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

electron scattering

$$R(q,\omega) \;=\; \sum_f \langle 0|\; \mathbf{j}^\dagger(q)\; |f\rangle\langle f|\; \mathbf{j}(q)\; |0\rangle\; \delta(w-(E_f-E_0))$$

$$R(q,\omega) \;=\; \int dt\; \langle 0|\; \mathbf{j}^\dagger(q)\;\; \exp[i(H-\omega)t]\; \mathbf{j}(q)\; |0\rangle$$

Full Response: Ground State (Hamiltonian)
Currents
Propagation for final states



Impulse Approximation for quasi-elastic
incoherent sum over single nucleons
requires momentum distributions and spectral functions

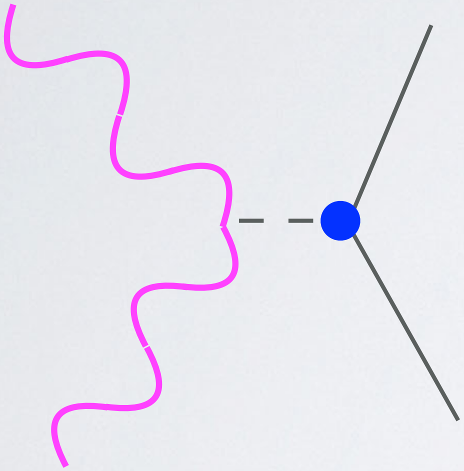
First required ingredient is scattering from an isolated nucleon

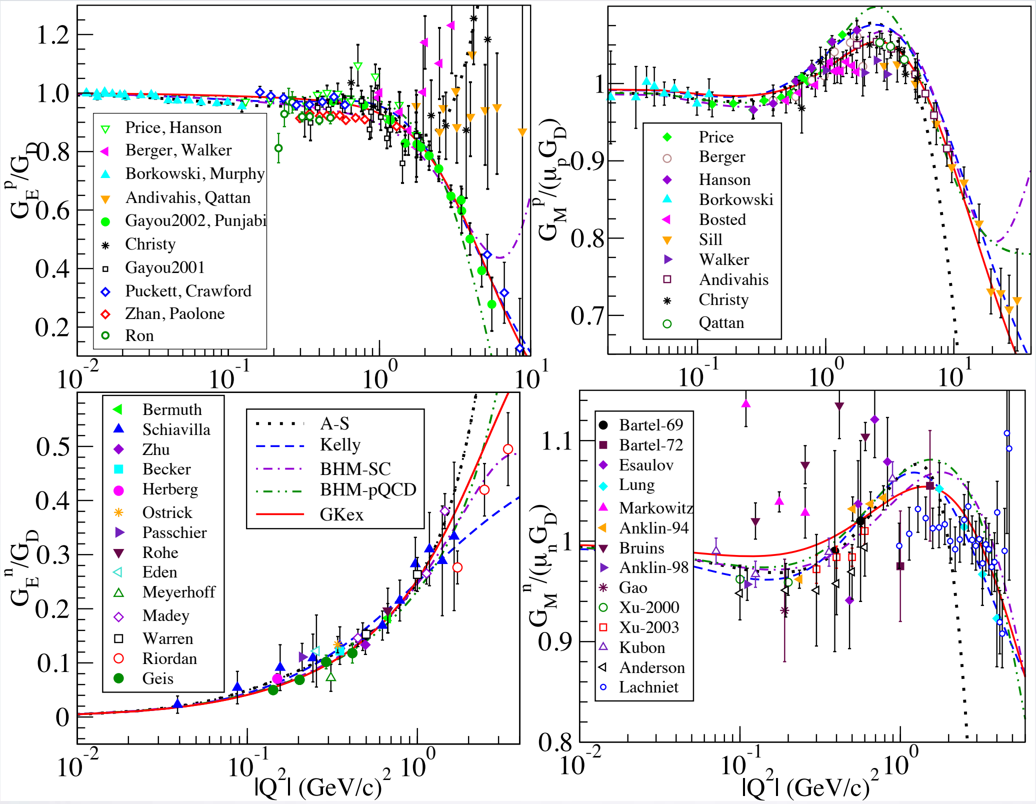
Electron and neutrino scattering from a single nucleon (or a set of independent nucleons)

experiment

theory (Lattice QCD)

EM Nucleon Form Factors

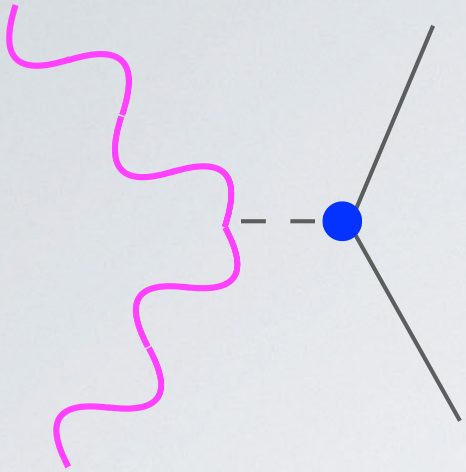




Gonzalex-Jiminez, Caballero, Donnelly, Phys. Reports 2013

Fairly well known for
q ≲ 1 GeV
but radius puzzle
near q=0

Nucleon Axial Form Factor



Theory: Lattice QCD

g_A can now be accurately calculated

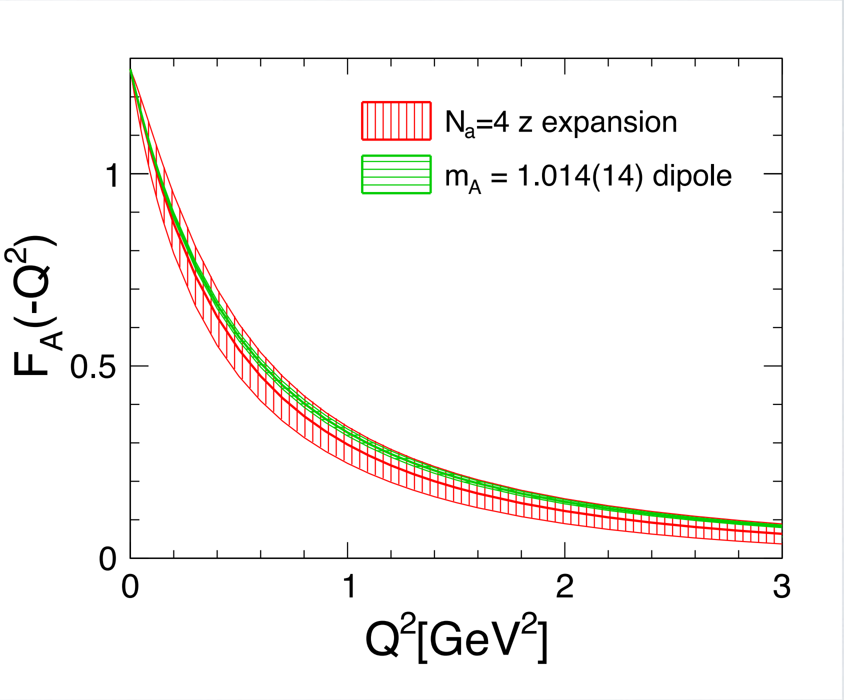
LANL, CalLAT, …

efforts underway for nucleon FF

FNAL, LANL, …

can and should be validated in EM sector

Deuterium analysis



$$r_A^2 \;=\; 0.46\ (0.22)\ \mathrm{fm}^2$$

Axial form factor from expt'l analysis
Meyer, Betancourt, Gran, Hill (2016)

Quasi-elastic scattering from the nucleus

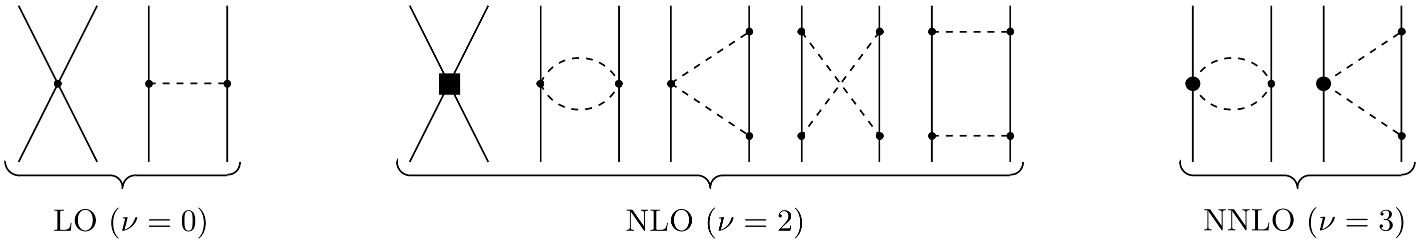
nuclear ingredients:
interactions
currents

experimental relations and scaling
momentum dependence (1st kind)
nuclear dependence (2nd kind)

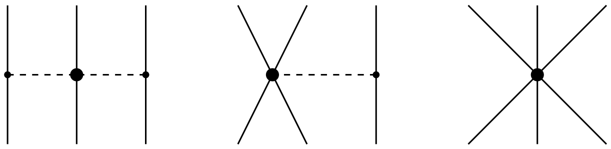
Nuclear Calculations:
Quantum Monte Carlo
Short-time, high-energy approximations
Tying to generators

Nuclear interactions and currents

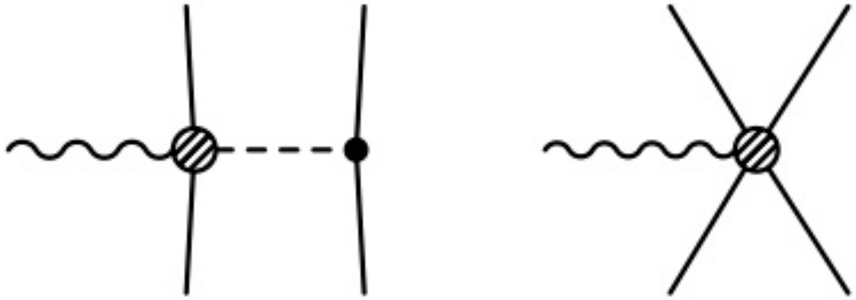
NN interactions



3N interactions



NN currents



Ab initio calculations of Nuclei

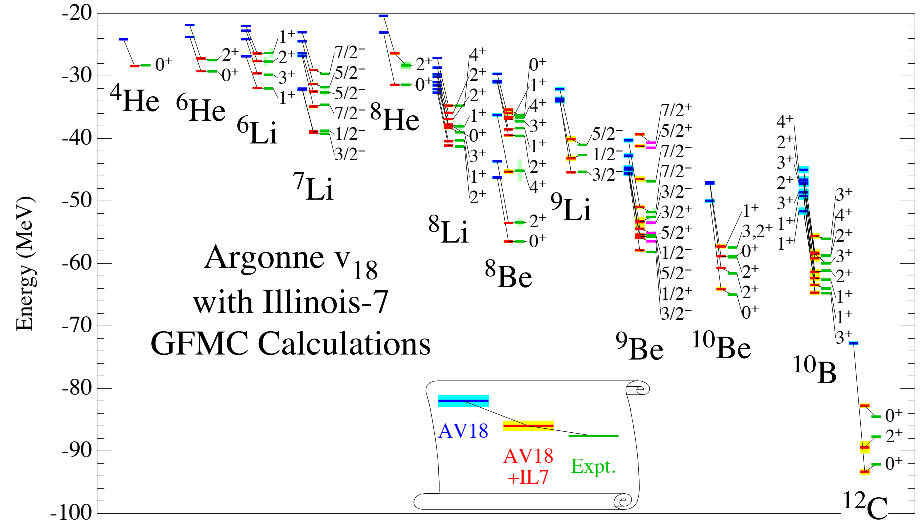
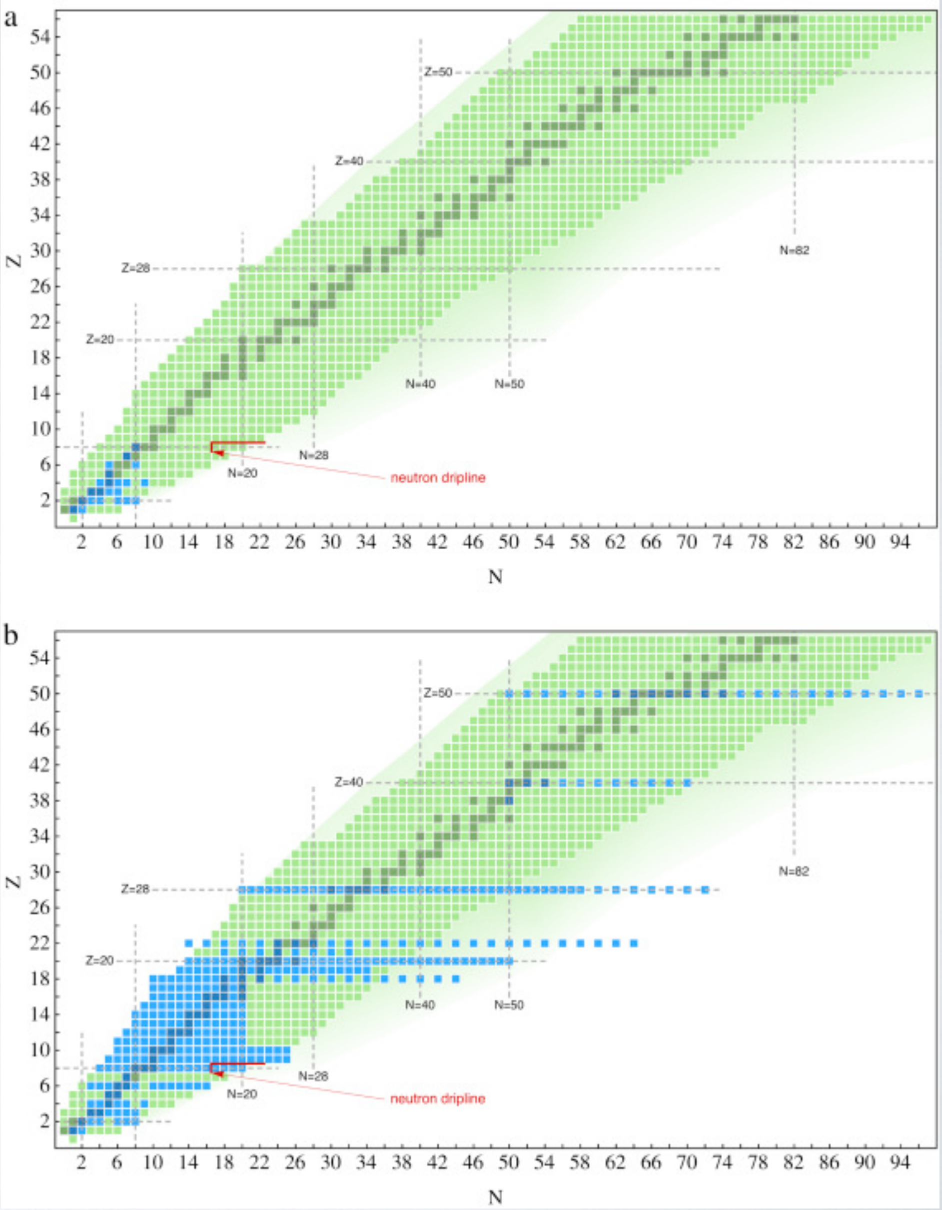


FIG. 2 GFMC energies of light nuclear ground and excited states for the AV18 and AV18+IL7 Hamiltonians compared to experiment.

Light Nuclear Spectra

Ab Initio Methods

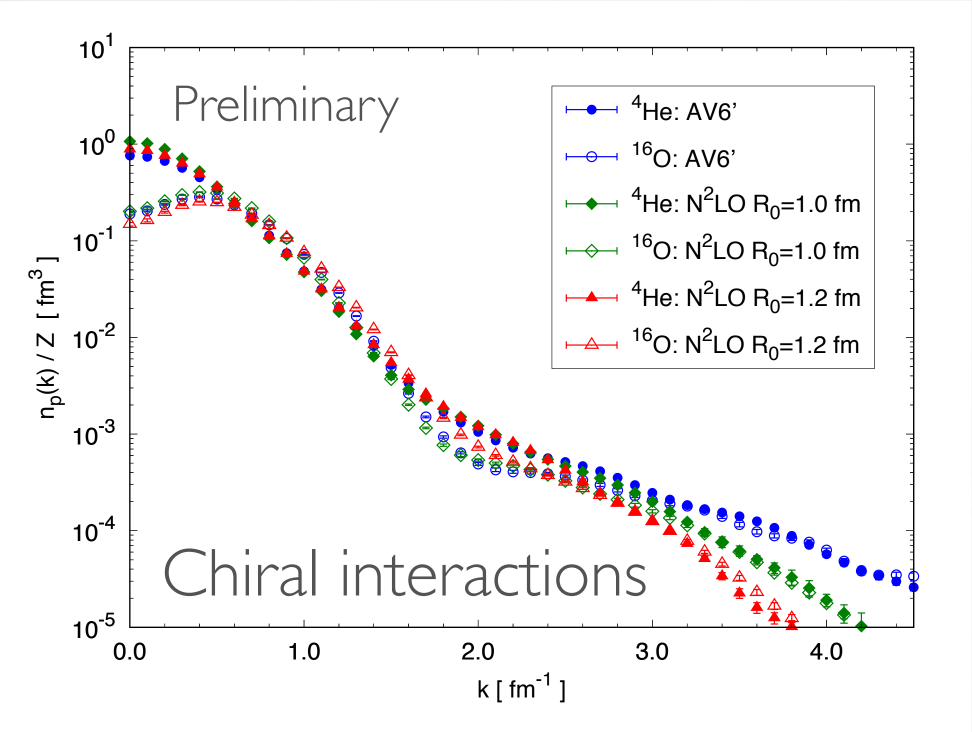


FRIB

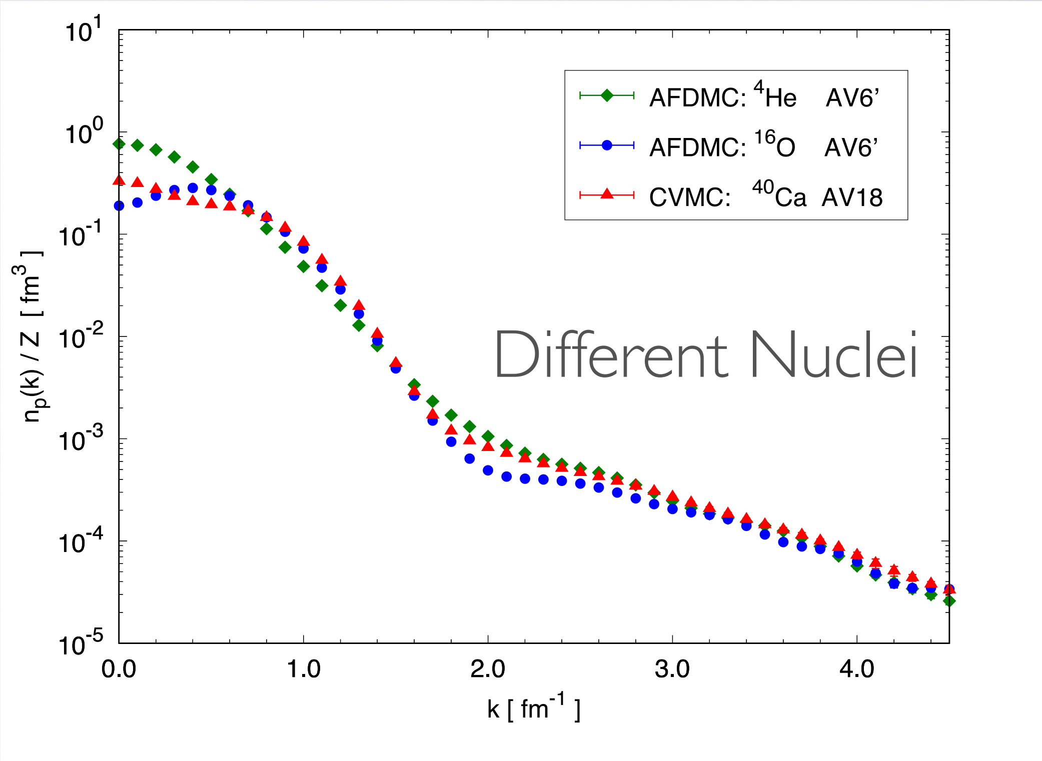
NUCLEI

Nuclear Computational Low-Energy Initiative

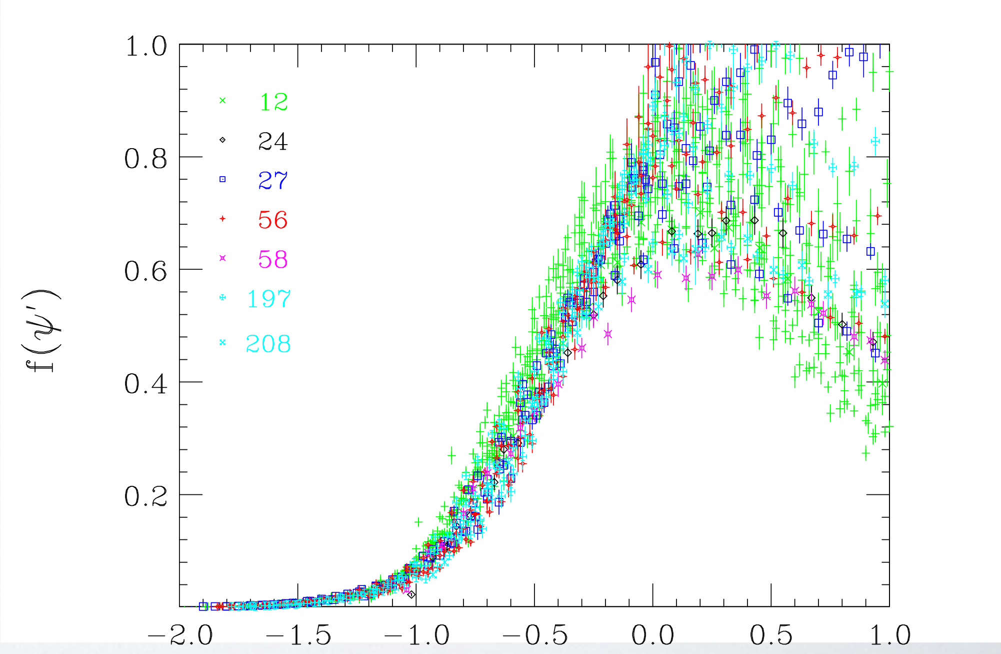
Single-Nucleon Momentum Distributions



Lonardoni, Lovato, Gandolfi, Wiringa, Pieper, et al

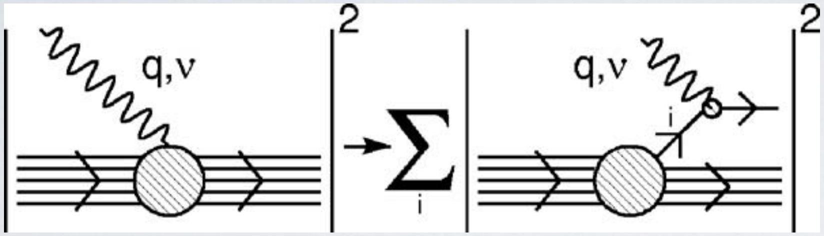


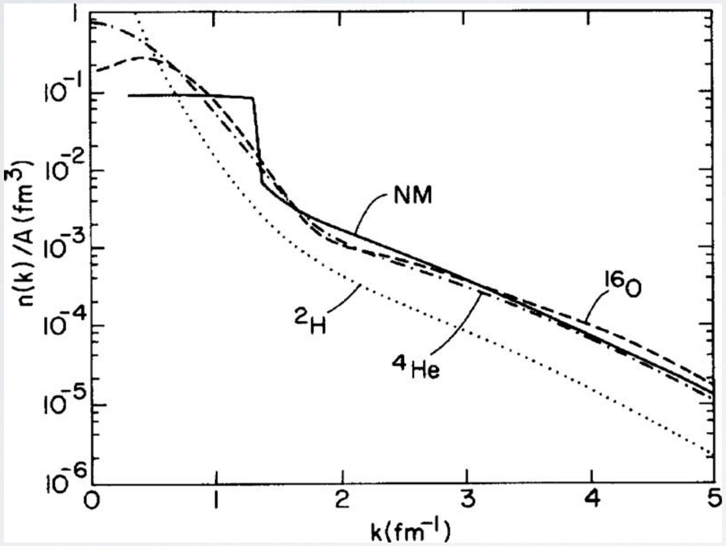
Integrated Strength:
15-20 % above k_F,
Amplitude ~ 0.3-0.4



Scaling of the 1st kind (w/ p)
Donnelly & Sick (1999)

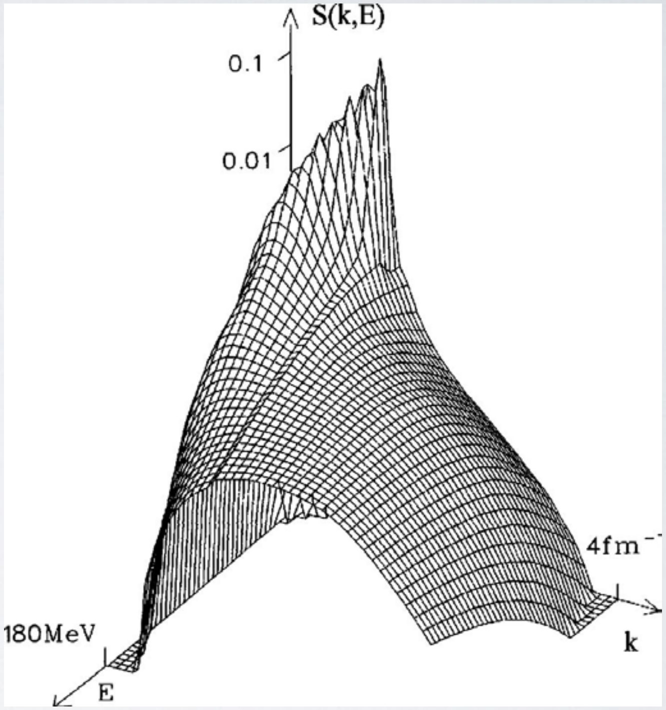
in PWIA: Response at different q requires knowledge of momentum Distributions or Spectral Functions





Schiavilla, et al 1986, Benhar, et al 1993

Spectral Function in NM

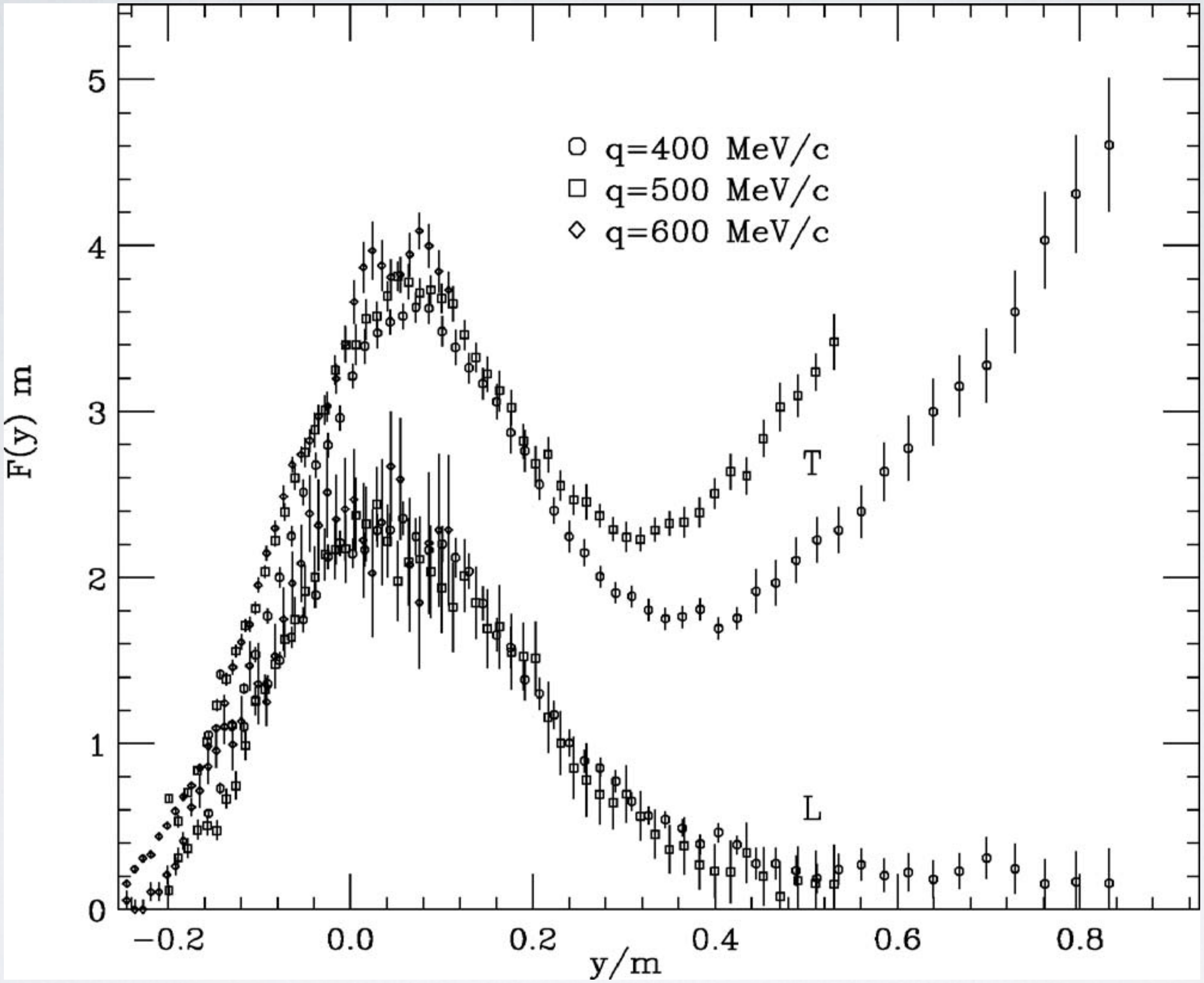


Benhar, 1989

Impulse Approximation for quasi-elastic
requires momentum distributions and/or spectral functions

One-body formulation gives equal longitudinal and transverse response
(once single-nucleon form factors divided out)

^{12}C transverse/longitudinal response



from Benhar, Day, Sick, RMP 2008
data Finn, et al 1984

scaling with momentum transfer better for individual responses
overall scale quite different for Transverse, Longitudinal responses

Electron Scattering:
Longitudinal and Transverse Response

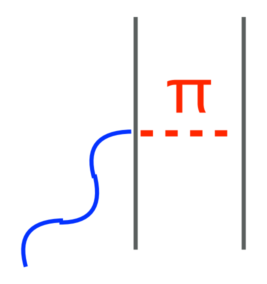
Transverse (current) response:

$$R_T(q,\omega) \ = \ \sum_f \langle 0|\ \mathbf{j}^\dagger(q)\ |f\rangle\langle f|\ \mathbf{j}(q)\ |0\rangle\ \delta(w-(E_f-E_0))$$

Longitudinal (charge) response:

$$R_L(q,\omega) \ = \ \sum_f \langle 0|\ \rho^\dagger(q)\ |f\rangle\langle f|\ \rho(q)\ |0\rangle\ \delta(w-(E_f-E_0))$$

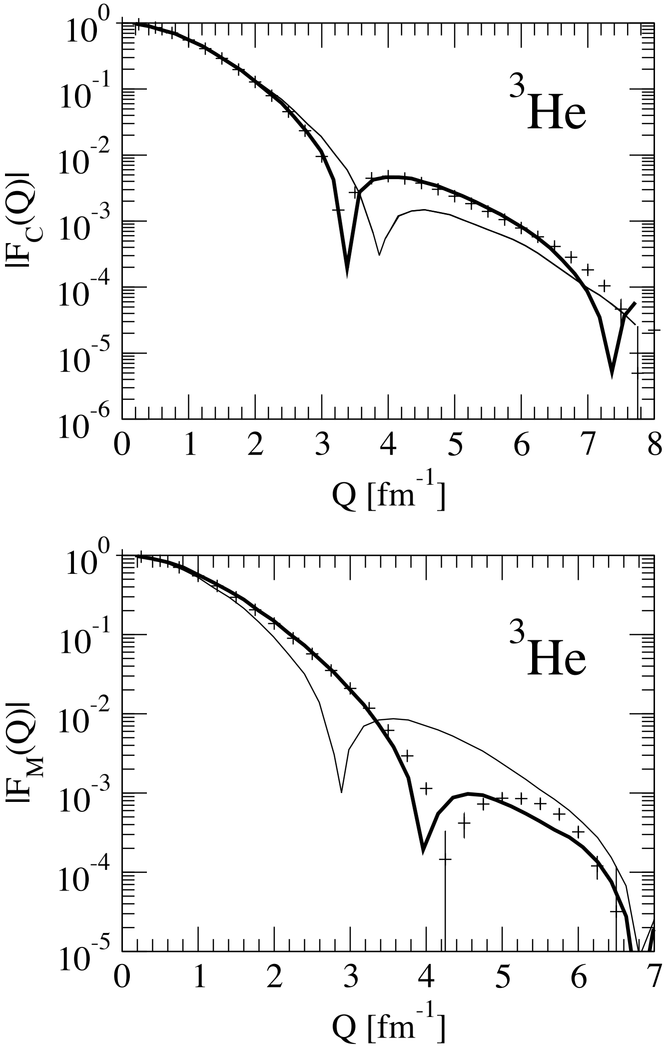
$$\mathbf{j} \ = \sum_i \ \mathbf{j}_i \ + \ \sum_{i<j} \ \mathbf{j}_{ij} + ...$$



Two-nucleon currents required by current conservation
Response depends upon all the excited states of the nucleus

2-Nucleon Currents critical to describe EM data

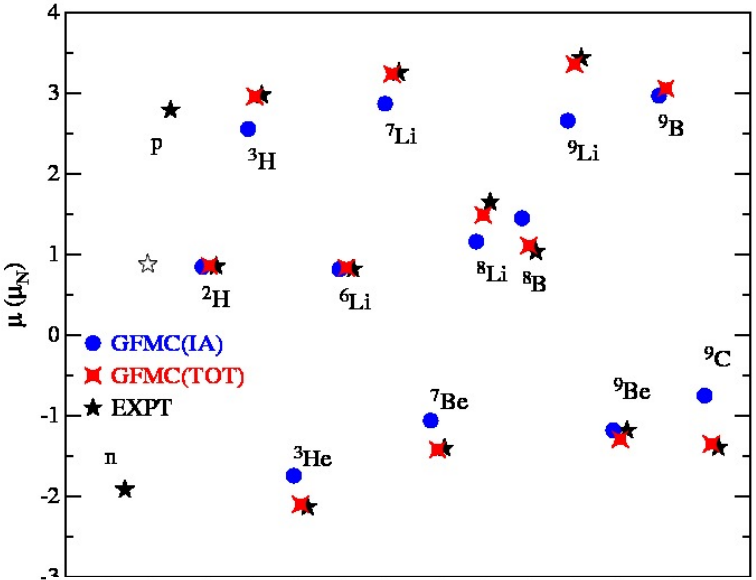
Form Factors



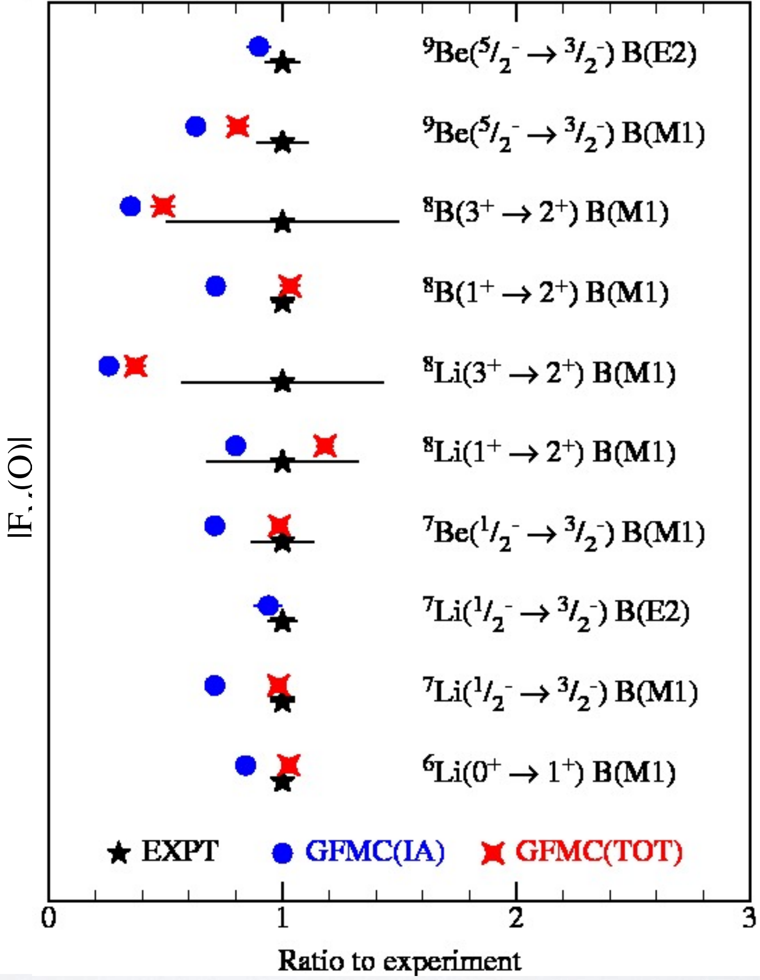
Wiringa, Pastore, Schiavilla, et al

see Pastore talk on Friday

Magnetic Moments



EM Transitions



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Sum Rules: Longitudinal Response

$$S\ (q)\ =\ \langle\ 0 \mid \mathbf{j}^\dagger(q)\ \mathbf{j}(q)\ 0\ \rangle$$

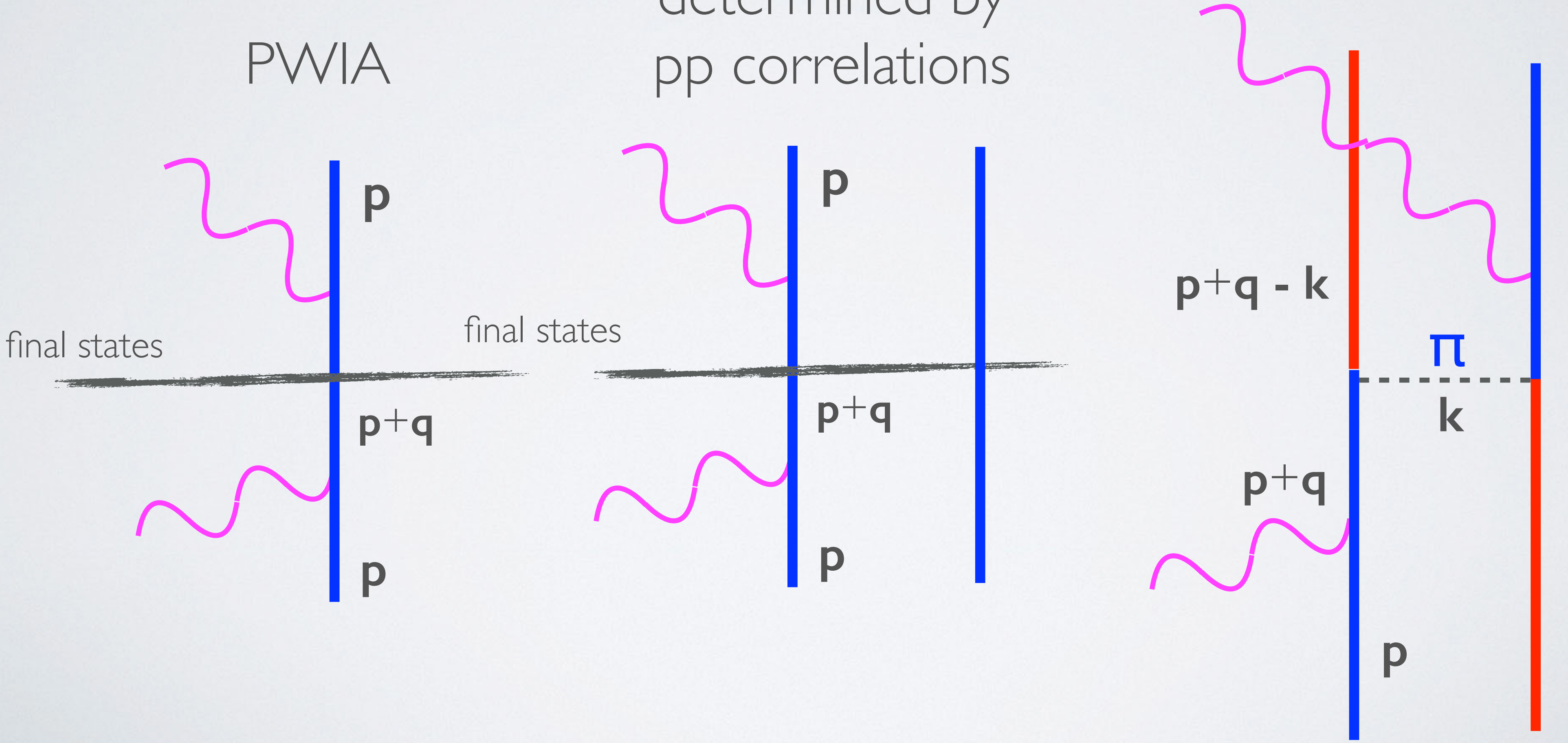
Gives an indication of total strength,
but not energy dependence

Longitudinal Channel

PWIA

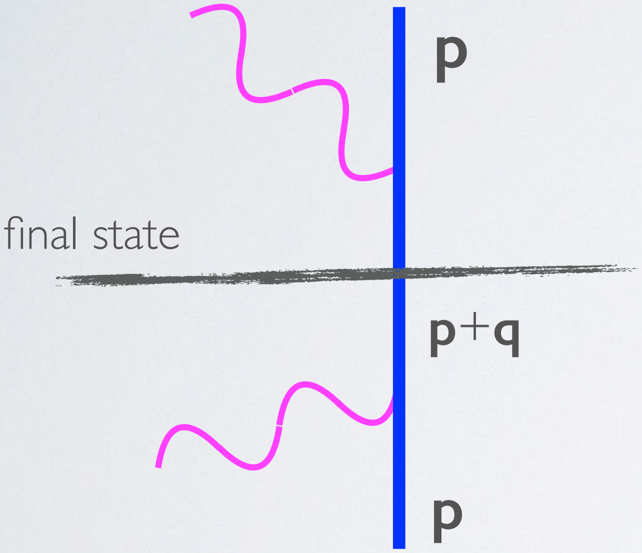
Sum Rule
determined by
pp correlations

Energy dependence
pion exchange
final state interaction

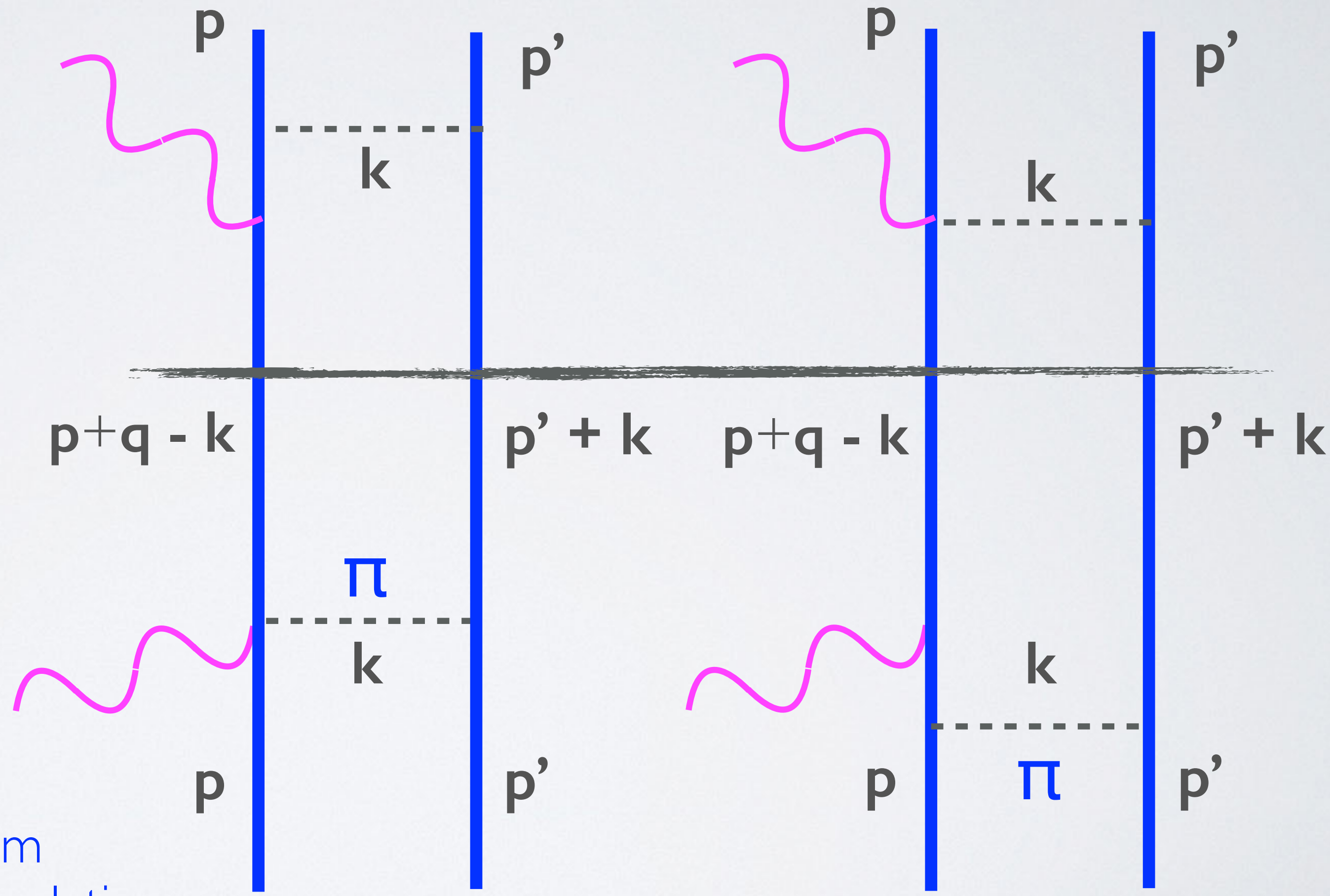


Quasielastic Scattering: Sum Rule for Vector Response

PWIA



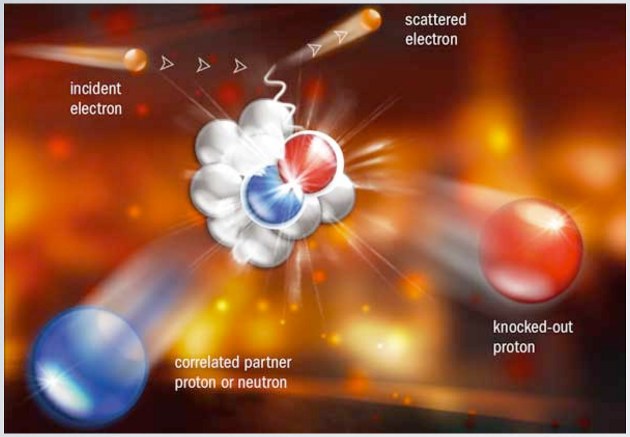
Sum Rule: Constructive Interference
between 1- and 2-body currents
w/ tensor correlations



Large enhancement from
combination of initial state correlations
and two-nucleon currents
similar in axial response

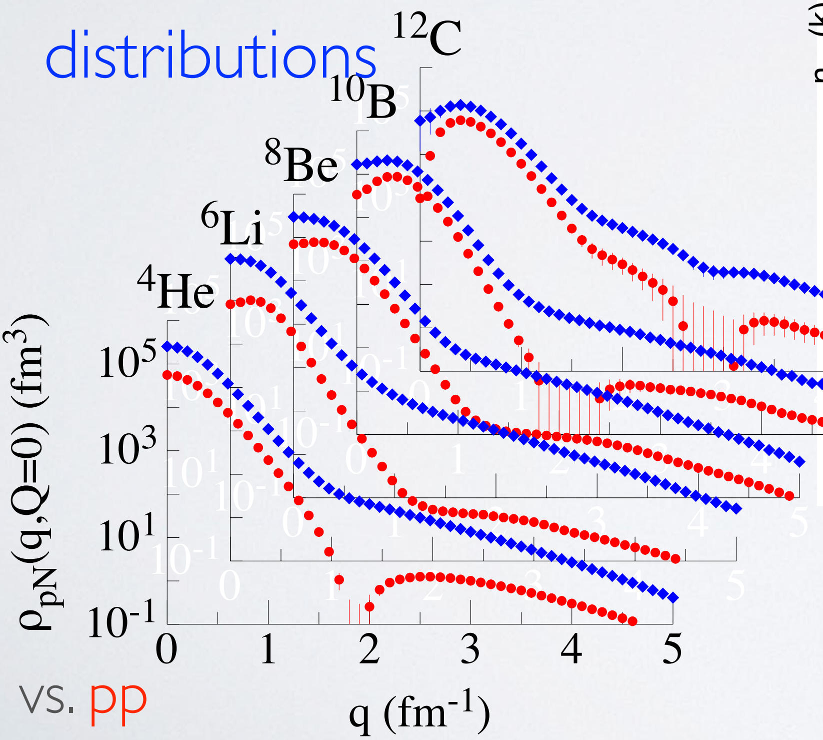
$$\propto \ \sigma_i \cdot \mathbf{k}\ \sigma_i \cdot \mathbf{q}\ (\sigma_j \cdot \mathbf{k})^2\ (\tau_i \cdot \tau_j)^2\ v_\pi^2(k)$$

Back to Back Nucleons (total Q~0)
np pairs dominate over nn and pp



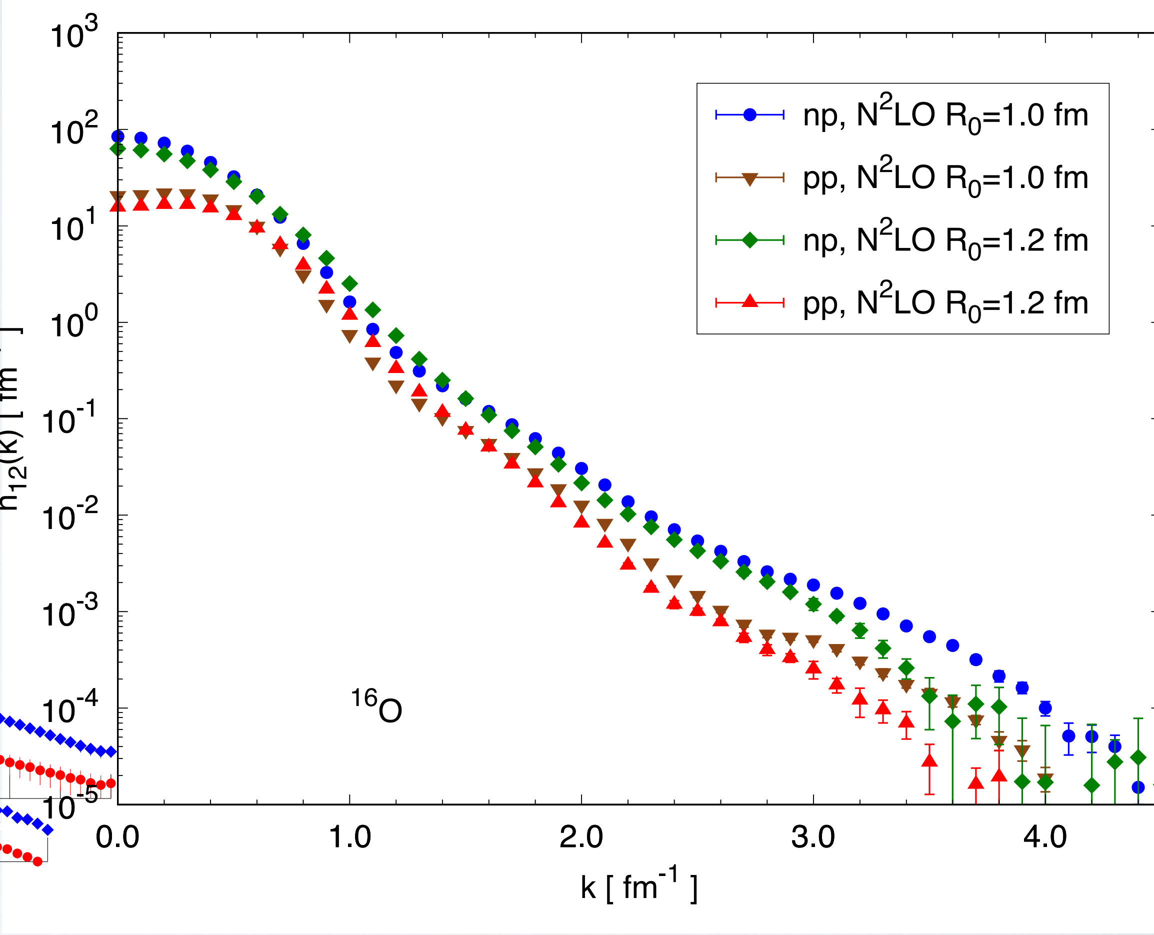
E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.
M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.
R Subedi *et al.* 2008 **Science 320** 1475.

2-nucleon momentum distributions



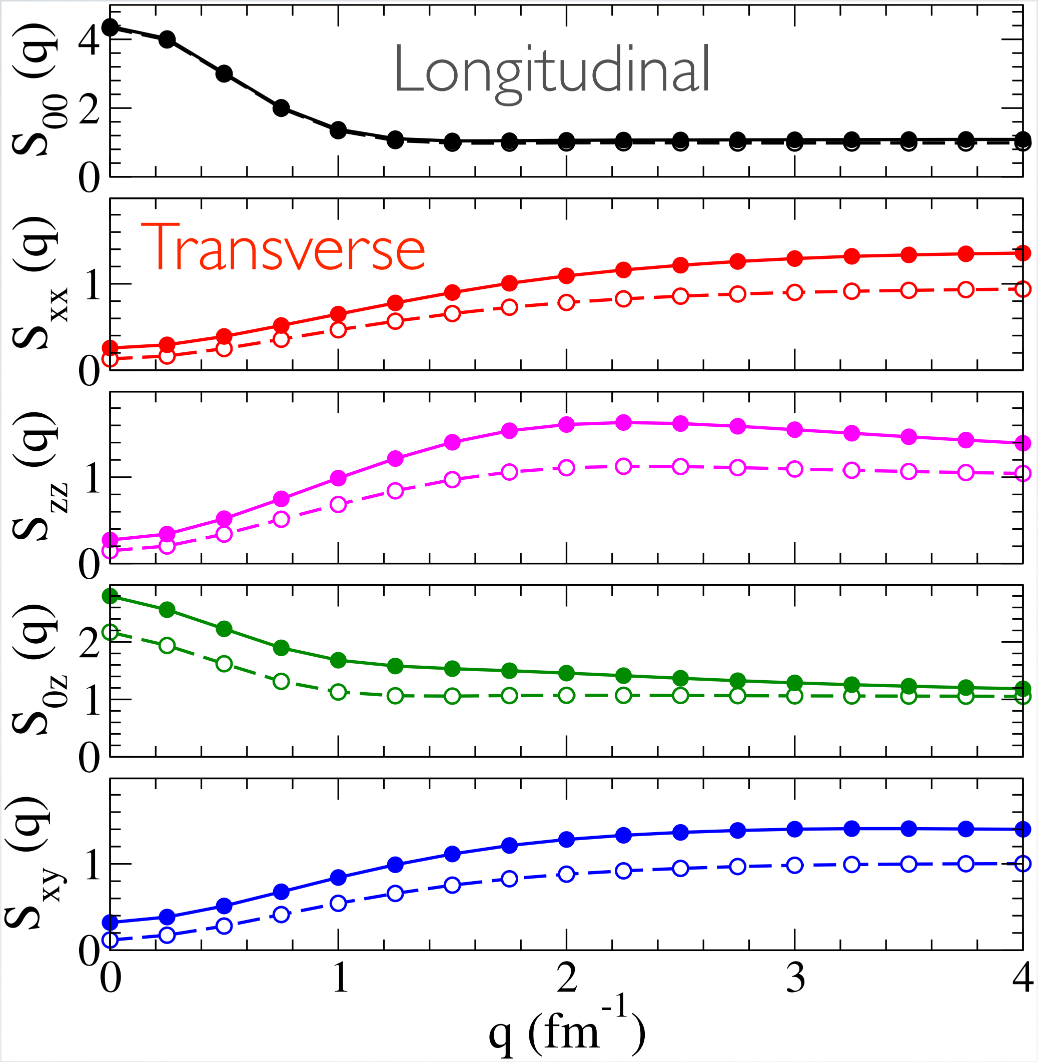
np vs. pp

Wiringa et al.; Carlson, et al, RMP 2015



Lonardoni, et al, preliminary

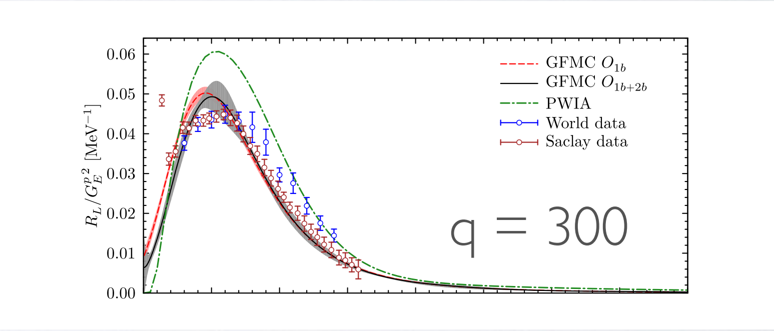
Sum rules in ^{12}C: neutral current scattering



EM

Note enhancement
in axial charge;
expected from
non-relativistic nature
of 2N currents
(as opposed to V)

Not always positive,
longitudinal response ^{12}C



Lovato, et. al PRL 2014

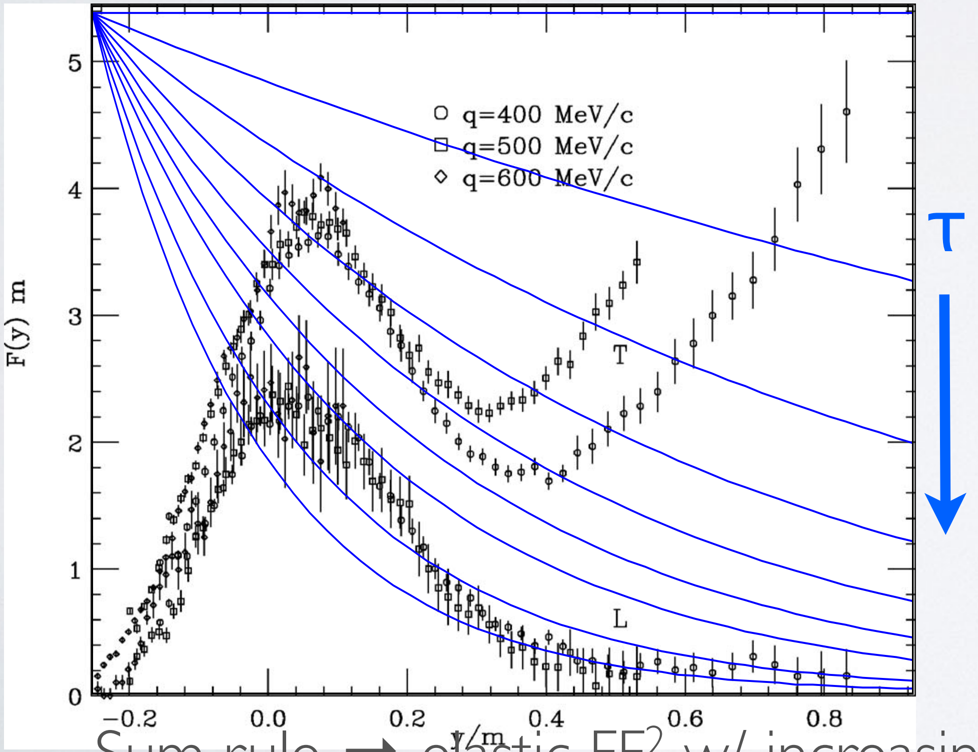
Single Nucleon currents (open symbols) versus
Full currents (filled symbols)

Euclidean Response

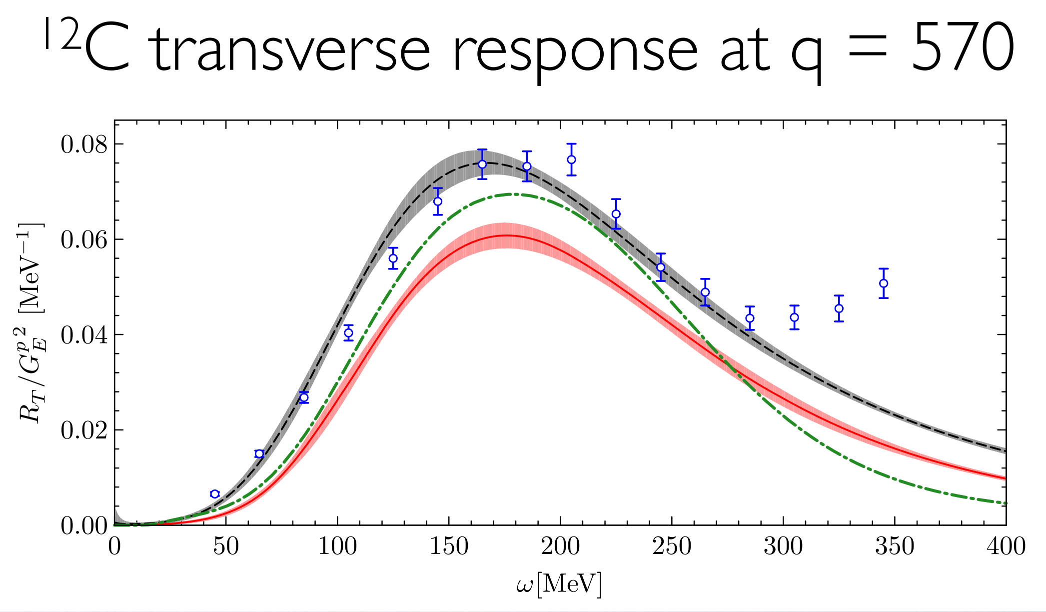
$$\tilde{R}(q,\tau) \;=\; \langle 0|\, \mathbf{j}^\dagger\ \exp[-(\mathbf{H}-\mathbf{E_0}-\mathbf{q^2}/(\mathbf{2m}))\tau]\ \ \mathbf{j}\ |\mathbf{0}\rangle >$$

- Exact given a model of interactions, currents
- `Thermal' statistical average
- Full final-state interactions
- `Local' Operator
- All contributions included - elastic, low-lying states, quasi elastic, …

Excellent agreement
w/ EM (L & T)
response in A=4,12
Lovato, 2015, PRL 2016

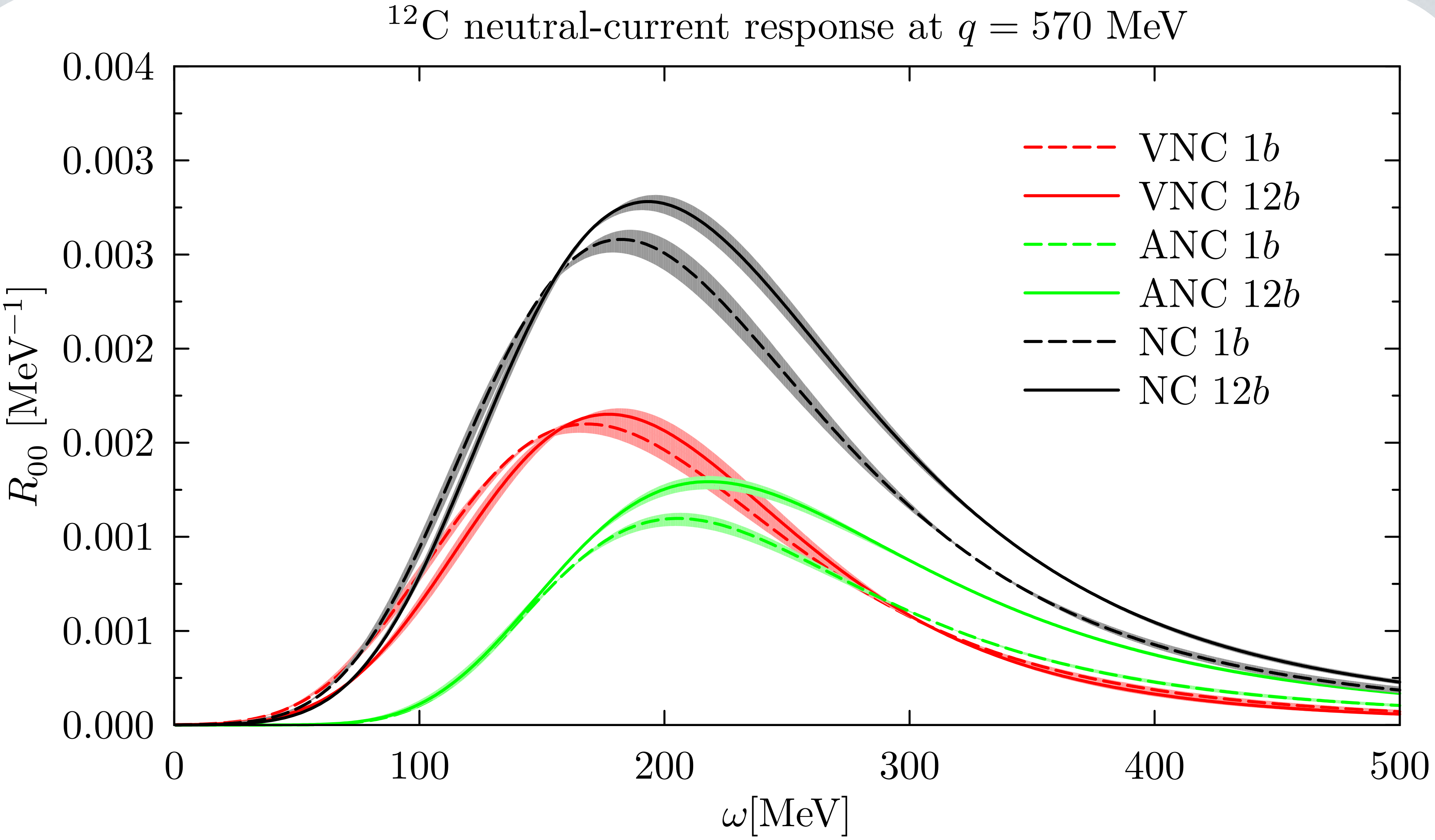


Sum rule → elastic FF^2 w/ increasing


^{12}C transverse response at q = 570

See A. Lovato's talk

Neutral Current Response of ^{12}C



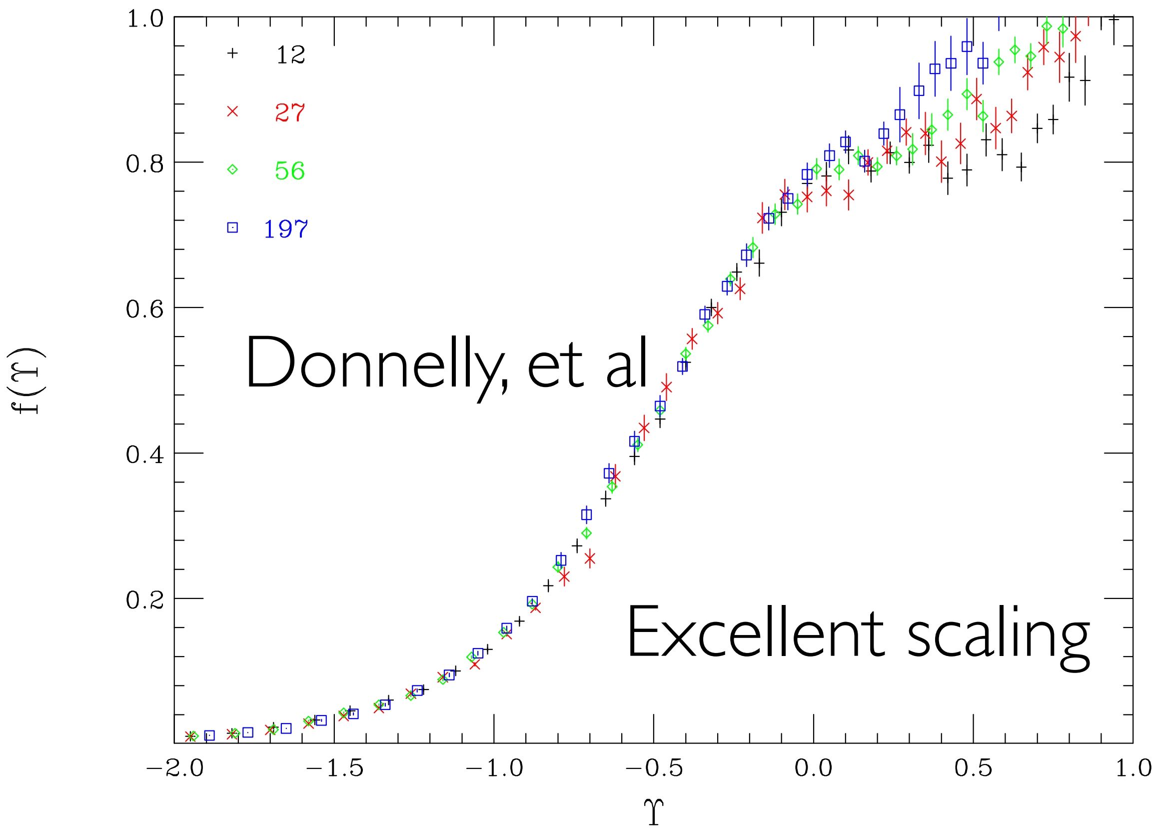
see Lovato talk on EM response

Lovato, et al, preliminary
charged current underway

Reaching toward larger A

Scaling of the 2nd kind;
fixed kinematics, different A

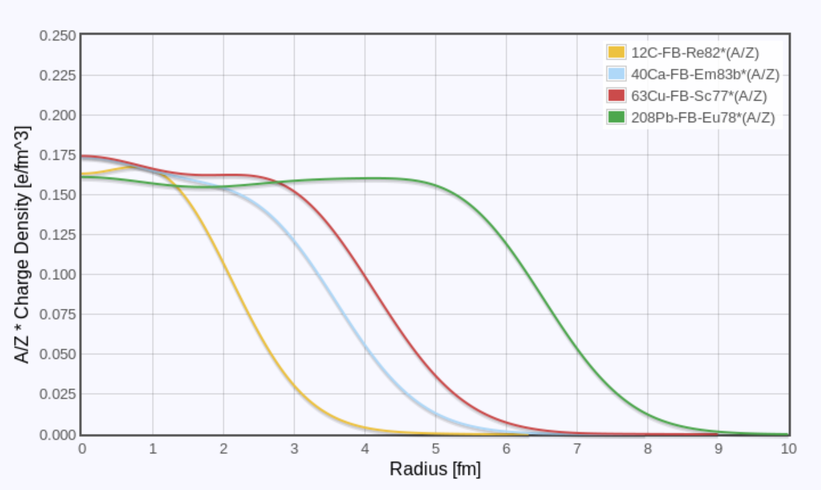
charge densities
for different nuclei



Donnelly, et al

Excellent scaling

slightly different k_F for different A

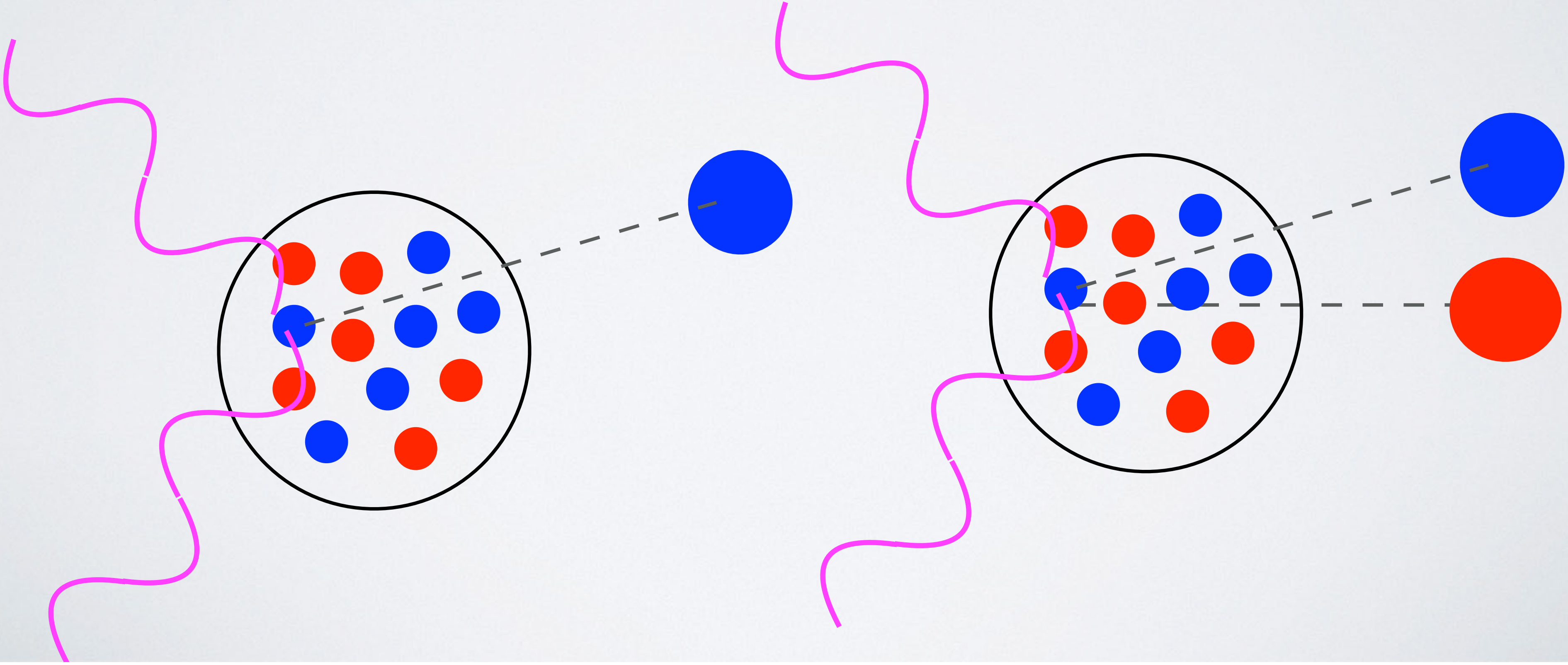


analysis of Hofstadter data

Larger A

Naive implementation of GFMC/AFDMC
will suffer from sign problem
Limited to quite short imaginary times

Exploring real-time propagation for short times:
short-time approximation (STA)
Employs factorization at two-nucleon level



Short Time - High Energy

$$R(q,\omega) = \sum_f \langle 0|O^\dagger(q)|f\rangle\langle f|O(q)|0\rangle\delta(\omega-(E_f-E_0))$$

$$R(\ q,\ \omega\ ) \ = \int dt\ \langle\ 0\ |\ j^\dagger(q)\ [\exp\ [i(H-\omega)t]]\ j(q)\ |\ 0\ \rangle$$

for short times (high energies):

$$P(t) \ = \ \exp[i(H-\omega)t] \ \rightarrow \prod_i \exp[i(H_i^0-\omega)t]\ \mathcal{S}\prod_{i<j}\frac{\exp[-H_{ij}t]}{\exp[-H_{ij}^0 t]}$$

H^0 : kinetic terms (one- and two-body)

gives PWIA in one-body limit

factorize and keep terms at two-body level:

$$j_1^\dagger(i)P(t)j_1^\dagger(i),\ j_1^\dagger(j)P(t)j(i),\ j_1^\dagger(j)P(t)j_2^\dagger(ij)+hc$$

write 2-nucleon state at vertex as interacting state
w/ relative momentum p and total momentum P

in principle can be extended to higher order in time t

Short Time - High Energy (cont'd)

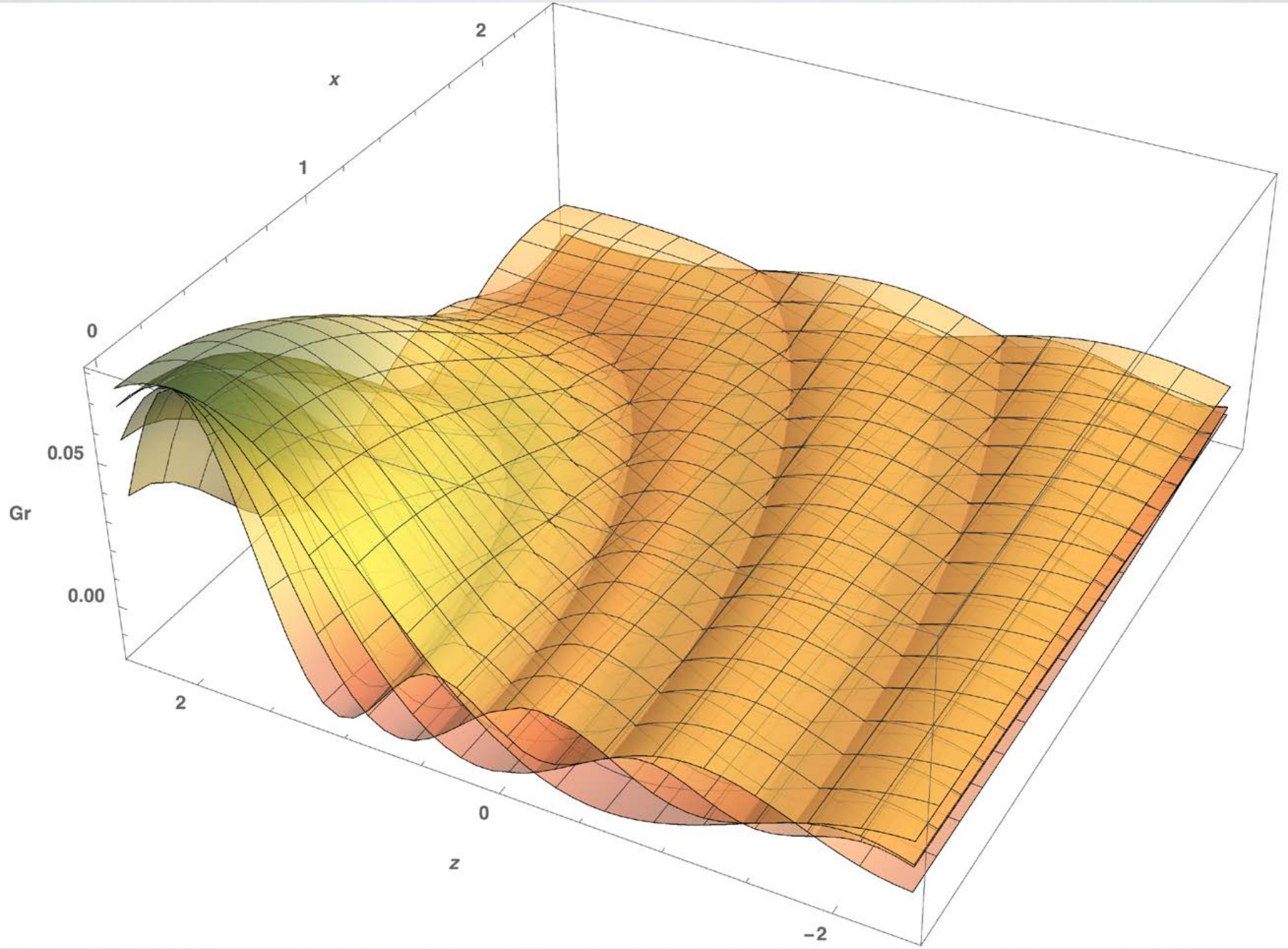
Advantages:

- Exact Sum Rules and Energy weighted sum rule
- Reduces to PWIA (1 or 2-nucleon level) if you ignore FSI
- Two-nucleon level - can in principle add relativity,
  pion prod, delta, …
- \`Local' operator : obeys scaling of 2nd kind for N=Z nuclei

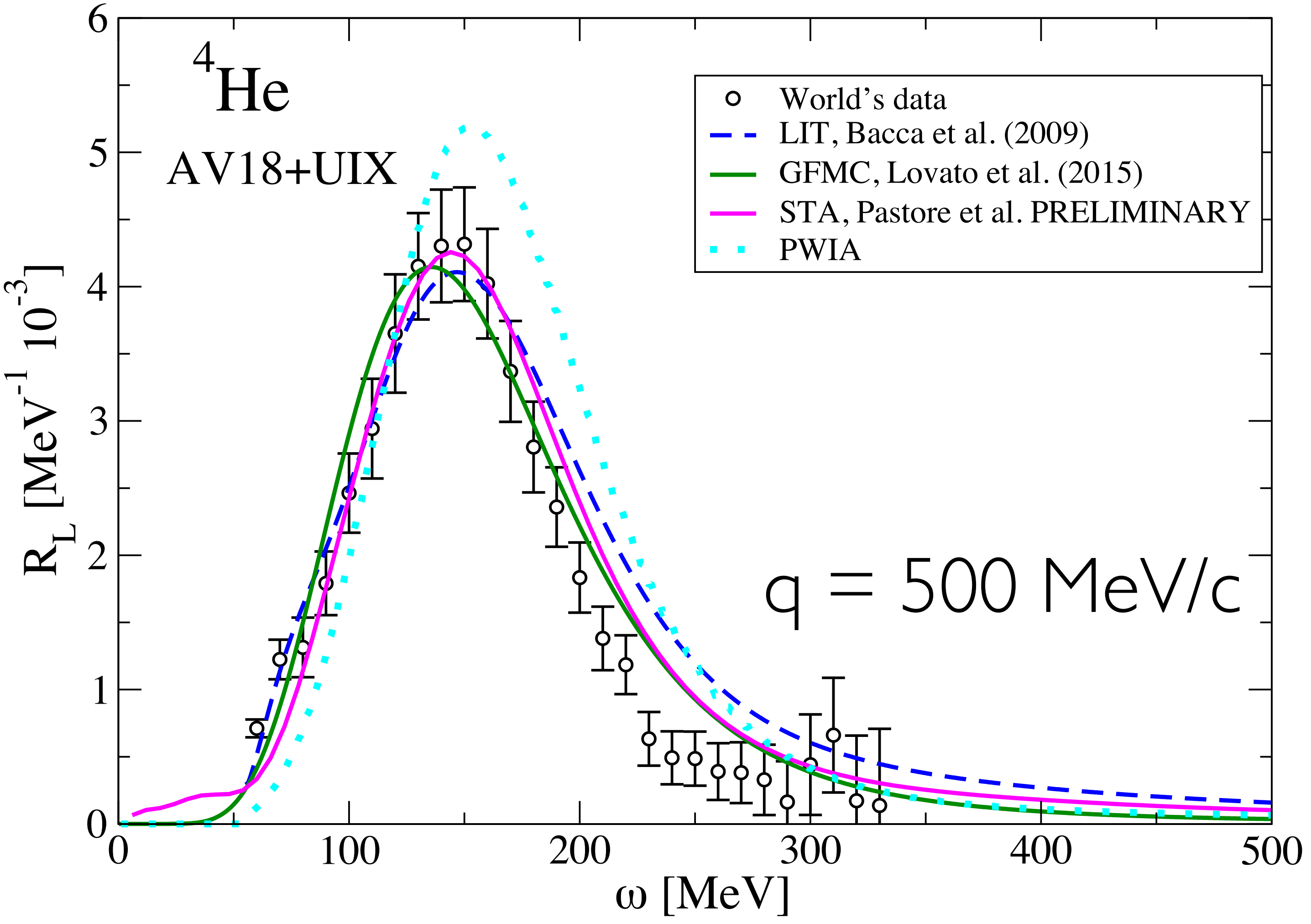
Disadvantage:

- Knows nothing about low-energy physics (giant resonances,…)
- Requires evaluation for each current operator

Short Time - High Energy (cont'd)



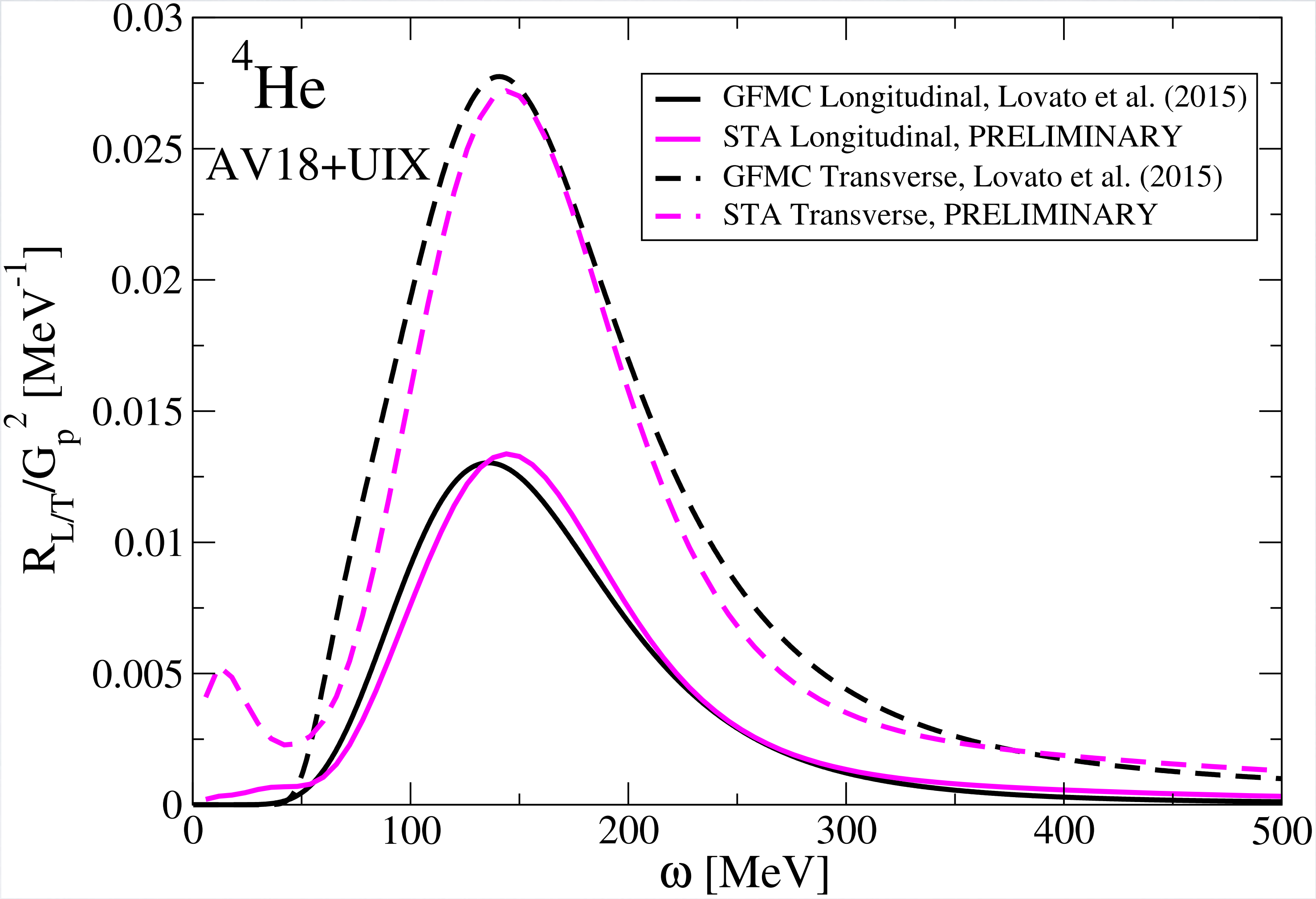
Longitudinal Response



Pastore, et al, preliminary

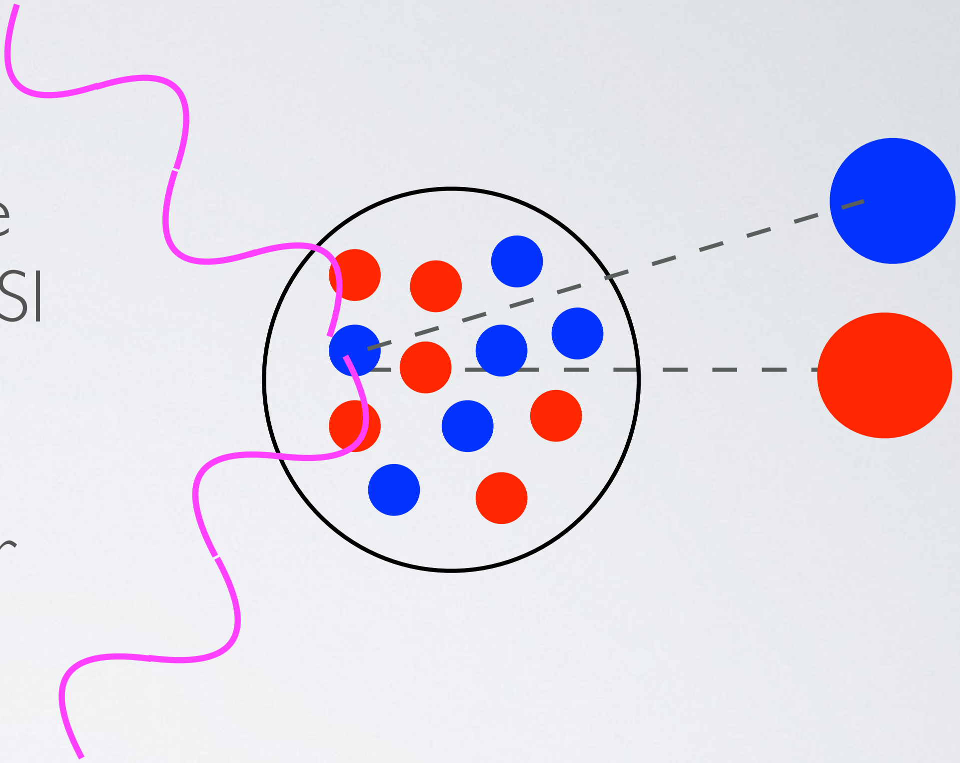
Similar approach using n(k1,k2) by N. Rocco, A. Lovato

Transverse Response



Larger A can be treated w/ full ground state, plus two-nucleon off-diagonal operator

Putting into Generators:



Quantum at the vertex:
- full 1- and 2-body interference
- inclusion of full two-nucleon FSI
- sum of positive contributions

Can match to classical generator after the vertex

Need to include
- full weak currents (at 2N level)
- relativistic effects
- pion/delta production

. . . .

Conclusion and Outlook:

- Coherent picture of neutrino-nucleus scattering within reach
- Requires 2N correlations, currents, final states
- Can be useful beyond overall constraint on integrated response
- Many related applications:
  - beta decay
  - double beta decay
  - astrophysical environments
  - …